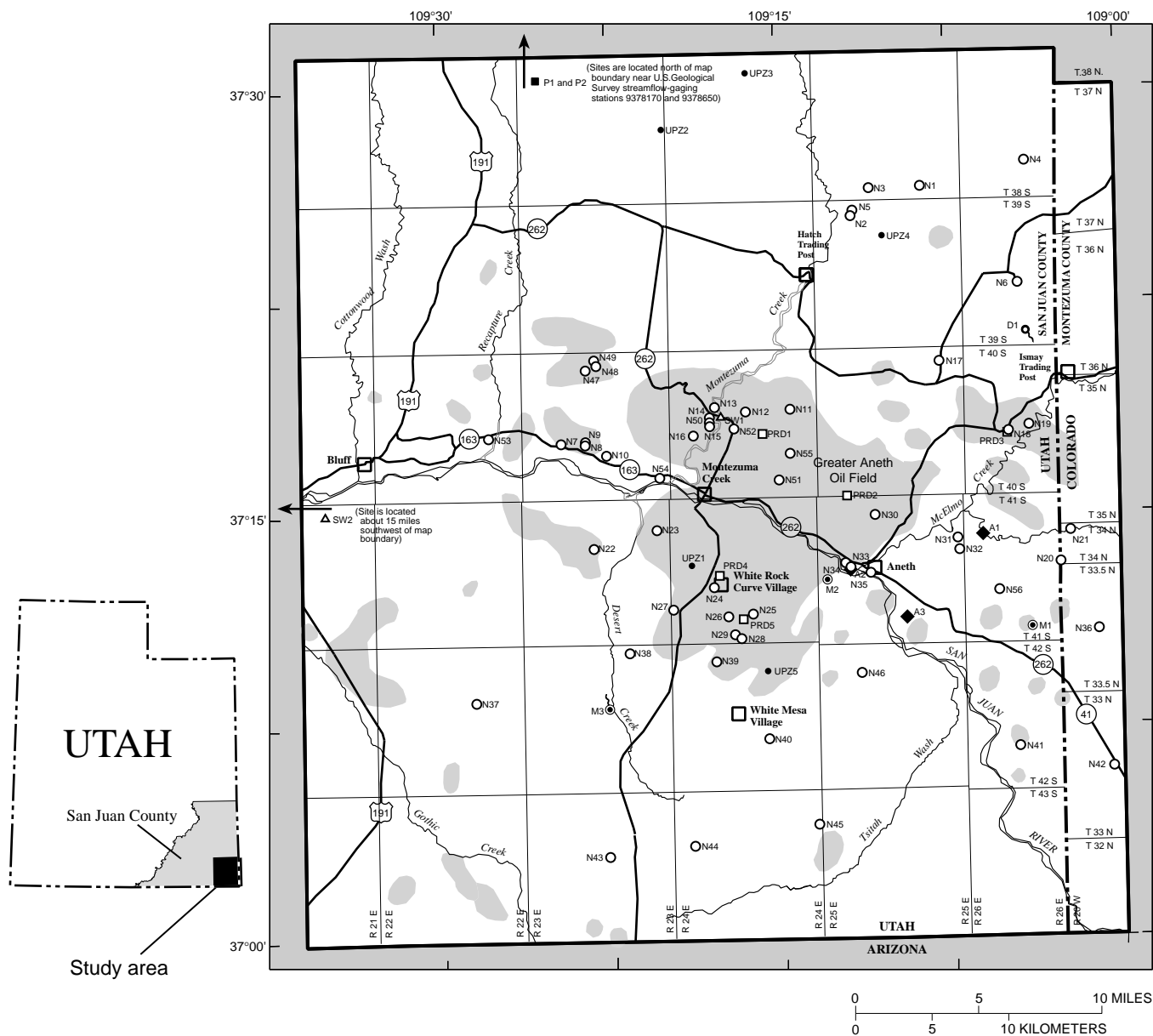


Hydrology, chemical quality, and characterization of salinity in the Navajo aquifer in and near the Greater Aneth Oil Field, San Juan County, Utah

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 96-4155



Prepared in cooperation with the
 U.S. ENVIRONMENTAL PROTECTION AGENCY,
 UTAH DIVISION OF OIL, GAS, AND MINING,
 BUREAU OF RECLAMATION,
 BUREAU OF LAND MANAGEMENT,
 BUREAU OF INDIAN AFFAIRS,
 NAVAJO ENVIRONMENTAL PROTECTION AGENCY, AND
 NAVAJO WATER RESOURCES MANAGEMENT DEPARTMENT



HYDROLOGY, CHEMICAL QUALITY, AND CHARACTERIZATION OF SALINITY IN THE NAVAJO AQUIFER IN AND NEAR THE GREATER ANETH OIL FIELD, SAN JUAN COUNTY, UTAH

By L.E. Spangler, D.L. Naftz, and Z.E. Peterman

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Bureau of Reclamation,
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Bureau of Indian Affairs,
Navajo Environmental Protection Agency, and
Navajo Water Resources Management Department**

**Salt Lake City, Utah
1996**



U.S. DEPARTMENT OF THE INTERIOR

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CONTENTS

Abstract	1
Introduction	2
Purpose and scope.....	2
Previous investigations	4
Acknowledgments	5
Description of study area.....	5
Geographic setting	5
Geologic setting	7
History of oil-field development	9
Water use in the study area	10
Hydrologic setting	11
Surface water	11
Ground water	13
The Navajo aquifer	14
Recharge	15
Discharge	15
Water-level declines.....	18
Potential for vertical movement	21
Potential avenues of ground-water movement	29
Sampling, analytical methods, and quality assurance	30
Chemical quality of ground water	34
Variations in salinity of water in the Navajo aquifer	58
Sources of salinity to the Navajo aquifer	60
Geochemical characterization of salinity in the Navajo aquifer	62
Bromide-to-chloride ratios	62
Iodide-to-chloride ratios.....	67
Oxygen and hydrogen isotopes	67
Strontium isotopes.....	73
Statistical similarity between ground-water samples.....	80
Results and need for additional data	84
Summary	86
References	87

PLATE

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1. Map showing quality of water from selected wells and springs in the Navajo and other aquifers in and near the Greater Aneth Oil Field, San Juan County, Utah

FIGURES

1. Map showing location of study area, physiographic features, and Greater Aneth and satellite oil fields, southeastern San Juan County, Utah 3
2. Diagram showing numbering system for geohydrologic-data sites in Utah..... 6
3. Schematic cross section of hydrogeologic units in the vicinity of the Greater Aneth Oil Field, southeastern San Juan County, Utah 8

FIGURES—Continued

4-7. Photographs showing:	
4. Outcropping strata of the Brushy Basin and Westwater Canyon Members of the Morrison Formation, capped by the Dakota Sandstone, in the Greater Aneth Oil Field, San Juan County, Utah.....	9
5. Navajo Nation windmill and holding tank near the Greater Aneth Oil Field, San Juan County, Utah.....	12
6. Hand-pump water well in alluvial deposits near Montezuma Creek in the Greater Aneth Oil Field, San Juan County, Utah	13
7. Abajo Mountains near Monticello, Utah, about 35 miles north of the study area, San Juan County, Utah	16
8. Map showing generalized potentiometric surface of the Navajo aquifer, directions of ground-water movement, and area where hydraulic head in upper Paleozoic aquifer is higher than that in Navajo aquifer, southeastern San Juan County, Utah	17
9. Photographs showing flowing water wells N30 (top) and N16 (bottom) in the Greater Aneth Oil Field, San Juan County, Utah.....	19
10. Map showing location of selected wells, springs, surface-water sites, precipitation sites, and brine-injection facilities in and near the Greater Aneth Oil Field, San Juan County, Utah.....	20
11. Box plots showing relation of the specific conductance of water from the Navajo aquifer from wells and springs in the State of Utah	37
12-20. Graphs showing:	
12. Variation in specific conductance of water from selected wells completed in the Navajo aquifer in and near the Greater Aneth Oil Field, San Juan County, Utah	59
13. Bromide and chloride concentration in water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, compared with the bromide-to-chloride weight ratio of modern standard mean ocean water.....	64
14. Bromide-to-chloride weight ratios compared with chloride concentration in end-member water groups in and near the Greater Aneth Oil Field, San Juan County, Utah.....	65
15. Mixing lines constructed between potential saline end-member water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, compared with bromide-to-chloride weight ratios in water from the Navajo aquifer with chloride concentrations greater than 60 milligrams per liter	66
16. Iodide-to-chloride weight ratios compared with chloride concentration in water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah	68
17. Mixing lines constructed between potential saline end-member water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, compared with iodide-to-chloride weight ratios in water from the Navajo aquifer with chloride concentrations greater than 60 milligrams per liter	69
18. The δD and $\delta^{18}O$ values of ground-water, surface-water, and snow samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, in relation to the North American and arid-zone meteoric water lines	71
19. Mixing lines constructed using the δD and $\delta^{18}O$ values of water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah.....	72
20. The δD and $\delta^{18}O$ values of water from wells completed in the Navajo aquifer in areas 1 and 2 in relation to the δD and $\delta^{18}O$ values of other water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah	74

FIGURES—Continued

21. Histograms showing the $\delta^{87}\text{Sr}$ values of oil-field brine and of water from the upper Paleozoic and Navajo aquifers, in and near the Greater Aneth Oil Field, San Juan County, Utah	75
22. Graph and map showing the relation of ground-water movement to $\delta^{87}\text{Sr}$ value of water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah	76
23. Map and graph showing the relation of $\delta^{87}\text{Sr}$ value of water from the Navajo aquifer to that of water from the upper Paleozoic aquifer, in and near the Greater Aneth Oil Field, San Juan County, Utah	79
24. Dendrogram and map showing the relation of hierarchical cluster analysis to wells completed in the Navajo and upper Paleozoic aquifers and to oil-field brine samples, in and near the Greater Aneth Oil Field, San Juan County, Utah	81

TABLES

1. Records of selected wells and springs in the Navajo and other aquifers in and near the Greater Aneth Oil Field, San Juan County, Utah	22
2. Analytical methods, reporting units, and minimum reporting levels for chemical constituents and physical properties analyzed in water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, 1989-94.....	31
3. Most probable standard reference water values for selected major- and trace-element constituents compared with the values for standard reference water samples submitted with samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, November 1992 to September 1994.....	33
4. Chemical analysis of selected minor- and trace-element constituents and physical properties from blank samples transported to and from the Greater Aneth Oil Field, San Juan County, Utah, November 1992 to April 1994	34
5. Chemical analysis of selected major-, minor-, and trace-element constituents from blank samples processed on site in and near the Greater Aneth Oil Field, San Juan County, Utah, November 1992 to September 1994.....	35
6. Chemical analysis of selected minor- and trace-element constituents and physical properties from duplicate samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, November 1992 to September 1994.....	36
7. Selected physical properties and major- and minor-chemical constituents in surface- and ground-water samples and precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah	38
8. Selected trace-element constituents and isotope values in surface- and ground-water samples and precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah....	52
9. Percentage of injection water determined from the $\delta^{18}\text{O}/\delta\text{D}$ isotopic mixing model compared with measured and calculated chloride concentration in water from selected wells completed in the Navajo aquifer in and near the Greater Aneth Oil Field, San Juan County, Utah.....	73
10. Percentage of injection water determined from selected $\delta^{87}\text{Sr}$ isotopic mixing models compared with measured and calculated chloride concentration in water from selected wells completed in the Navajo aquifer in and near the Greater Aneth Oil Field, San Juan County, Utah.....	78
11. Data set ANETH used in multivariate statistical analysis	82

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	0.0254	meter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
mile (mi)	1.609	kilometer
square mile (mi ²)	2.590	square kilometer
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.0631	liter per second
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per day (acre-ft/d)	0.001233	cubic hectometer per day
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$^{\circ}\text{F} = 9/5(^{\circ}\text{C}) + 32.$$

Degree Fahrenheit (°F) may be converted to degree Celsius (°C) by using the following equation:

$$^{\circ}\text{C} = 5/9(^{\circ}\text{F} - 32).$$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 — a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Chemical concentration and water temperature are reported only in metric units. Chemical concentration is reported in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million. Specific conductance is reported in microsiemens per centimeter (µS/cm) at 25 degrees Celsius.

Hydrology, chemical quality, and characterization of salinity in the Navajo aquifer in and near the Greater Aneth Oil Field, San Juan County, Utah

By L.E. Spangler, D.L. Naftz, and Z.E. Peterman

ABSTRACT

Because of the concern of potentially increasing salinity in freshwater aquifers in the vicinity of the Greater Aneth Oil Field in southeastern San Juan County, Utah, a hydrologic and geochemical study was done to determine the extent and concentrations of salinity in the freshwater aquifers, to document changes in salinity throughout time, and to identify, if possible, the source and potential pathways of the saline water.

The Navajo aquifer is the principal bedrock aquifer in the vicinity of the Greater Aneth Oil Field and includes the Entrada, Navajo, and Wingate Sandstones. The Navajo aquifer is confined in this area, and wells typically discharge water at land surface. The Navajo aquifer generally ranges from 750 to 1,000 feet in thickness, with the top of the aquifer averaging 550 feet below land surface.

The Navajo aquifer is recharged along the flanks of the Abajo Mountains, Sleeping Ute Mountain, and the Carrizo Mountains, to the north, east, and south of the study area, respectively. Potentiometric contours, increasing hydraulic head with depth, and gains in discharge indicate that water in the Navajo aquifer moves downgradient from these recharge areas and discharges into the San Juan River.

Water from the Navajo aquifer is discharged primarily from water wells, and dry holes and previously producing oil wells that were plugged back to water-bearing formations. Measured discharge from flowing wells during the study ranged from less than 1 to as much as 150 gallons per minute. About 600 acre-feet of water discharged from the Navajo aquifer from flowing wells during 1992-93. Water-level declines in some Navajo aquifer wells have been as much as 178 feet since the 1950s.

Dissolved-solids concentrations in water from 56 wells in the Navajo aquifer ranged from 145 milligrams per liter (fresh) to as much as 17,300 milligrams per liter (very saline). Water from most wells shows less than 10-percent variation in salinity with time; however, increases of greater than 50 percent have been documented for selected wells. Water with dissolved-solids concentrations greater than 10,000 milligrams per liter may be less than 500 feet below land surface in the Aneth area.

High levels of salinity in water from some water wells prior to the late 1950s indicate that saline water was present in the Navajo aquifer before development of the Greater Aneth Oil Field. Salinity in the Navajo aquifer may have been derived from upward movement of saline water from the upper Paleozoic aquifer or possibly from localized dissolution of evaporites that were present in the Navajo aquifer. Apparent increases and decreases in salinity of water from selected wells could be caused by pumping or wellbore effects. Potential upward movement of water from the upper Paleozoic aquifer into the Navajo aquifer may take place in an area near Aneth where the hydraulic head in the upper Paleozoic aquifer exceeds that in the Navajo aquifer.

Mixing model results indicate that the bromide- and iodide-to-chloride weight ratios characteristic of oil-field brine in the study area decrease with increasing chloride concentration in water from the Navajo aquifer, and generally follow the end-member mixing lines constructed with the mean non-oil-field brine and the upper Paleozoic aquifer end-member water compositions. Neither oil-field brine nor comingled injection water is the source of salinity to the Navajo aquifer.

The $\delta^{18}\text{O}$ and δD values of water samples from the Navajo aquifer north of the San Juan River are distinctly lighter than the $\delta^{18}\text{O}$ and δD values of water samples from the Navajo aquifer east and south of the San Juan River. This difference is possibly caused by geographic segregation of water in the aquifer and not by mixing with oil-field brine. The $\delta^{87}\text{Sr}$ values of oil-field brine samples are substantially smaller than the values of water samples from the Navajo aquifer, indicating that oil-field brine is not a source of salinity. The $\delta^{87}\text{Sr}$ values of water samples from the upper Paleozoic aquifer are similar to the mean isotopic composition of the more saline water from the Navajo aquifer and indicate that the upper Paleozoic aquifer is a possible source of salinity. Hierarchical cluster analysis using chemical constituents in 43 water samples from the Navajo aquifer, 4 water samples from the upper Paleozoic aquifer, and 5 oil-field brine samples indicates that oil-field brine is not the salinity source to the Navajo aquifer and that water from the upper Paleozoic aquifer may be a source of salinity.

INTRODUCTION

During a study of ground water in bedrock aquifers in eastern San Juan County, Utah, Avery (1986, p. 36) noted that water from the Navajo and other sandstones of Mesozoic age near Aneth, Utah (fig. 1), had higher-than-expected salinity in comparison to water from the same formations in other parts of southern and southeastern Utah and adjacent areas in Colorado, Arizona, and New Mexico. Analyses of water from wells drilled by Texaco, Inc. during the late 1950s also documented anomalously high levels of salinity in ground water in the vicinity of Montezuma Creek and Aneth, Utah (J.R. Barnes, consulting geologist, unpub. data, 1959, table 3, p. 18). In addition, changes in quality of water from selected wells throughout time have been reported by residents of the area. Results of analysis of water samples collected from 1989 to 1994 have indicated that most of the affected water wells are in and near the Greater Aneth Oil Field (fig. 1). Brines associated with oil production in the Greater Aneth Oil Field are generally injected back into the producing oil formations for secondary recovery of oil and have been suggested as the potential source of the saline water in the Montezuma Creek area (Kimball, 1992, p. 89).

Brines generally contain very high concentrations of dissolved solids, including numerous trace- and major-inorganic constituents and trace-organic compounds that can adversely affect drinking-water supplies (Thurman, 1985; Surdam and MacGowan, 1987; and Shipley, 1991). Because of the concern of potentially increasing salinity in freshwater aquifers in the vicinity of the Greater Aneth Oil Field, the U.S. Geological Survey in cooperation with the U.S. Environmental Protection Agency; Utah Division of Oil, Gas, and Mining; Bureau of Reclamation; Bureau of Land Management; Bureau of Indian Affairs; Navajo Environmental Protection Agency; and the Navajo Water Resources Management Department did a hydrologic and geochemical study to determine the extent and concentrations of saline water in the freshwater aquifers, to document changes in salinity throughout time, and to identify, if possible, the source(s) and potential pathways of the saline water.

The saline source(s) leading to increasing concentrations of dissolved solids in fresh ground-water systems is difficult to determine when more than one potential source exists; however, this type of information is needed by regulatory agencies to develop plans to prevent future increases in salinity and to remediate existing salinity problems. As non-saline ground water becomes more important for domestic use in areas with limited ground-water supplies, an understanding of the processes of salinization and establishment of base-line water quality becomes increasingly important.

Purpose and Scope

This report describes the results of an investigation to determine the extent and concentrations of saline water in the principal freshwater aquifers, document changes in salinity throughout time, and identify the source(s) and potential pathways of saline water in the vicinity of the Greater Aneth Oil Field in southeastern San Juan County, Utah. Objectives include determination of the directions of ground-water movement in the principal aquifers in the study area; identification of conservative and nonconservative inorganic, organic, and isotopic geochemical constituents that can be used to define the source(s) and pathway(s) of movement of saline water in the principal freshwater aquifers; using geochemical data in end-member mixing models and pattern-recognition techniques to identify and quantify source(s) of saline water in the principal freshwater aquifers; and determination of the saliniza-

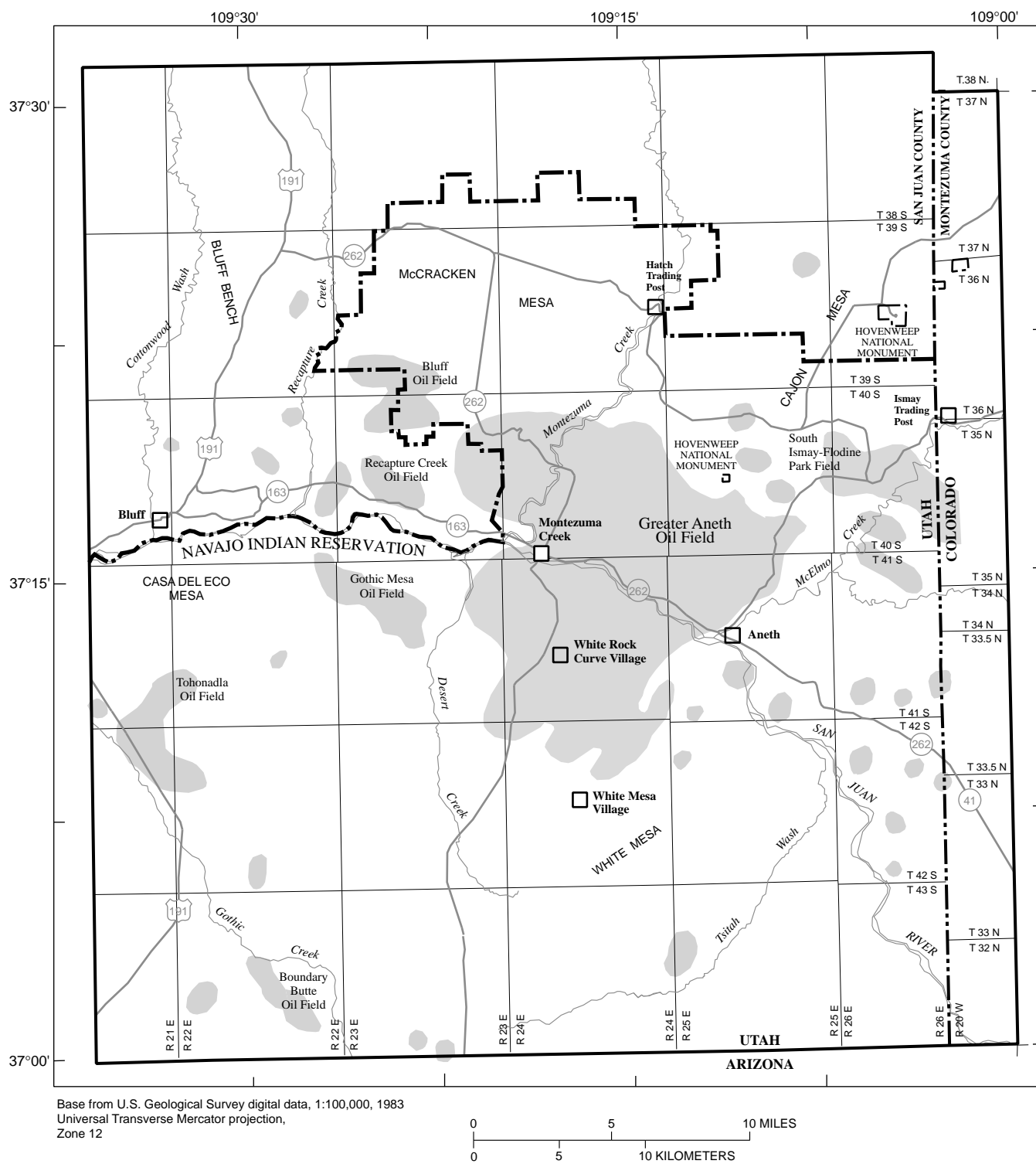


Figure 1. Location of study area, physiographic features, and Greater Aneth and satellite oil fields, southeastern San Juan County, Utah.

tion process(es). Results of the study will enable the Navajo Nation as well as the principal operators in the Greater Aneth Oil Field and vicinity to better understand the hydrology and water quality of the principal aquifers so that ground-water resources can be properly managed and adequately protected.

Water-quality, discharge, water-level, and well-record data were obtained from U.S. Geological Survey data bases. Well data also were obtained from the Navajo Nation Water Resources Management Department; the Utah Division of Oil, Gas, and Mining; the Bureau of Land Management; and oil companies operating in the study area. Additional water-quality, discharge, water-level, and well-record data were collected, measured, and obtained from 1989 to 1994. A data base consisting of 52 water samples was used in multivariate statistical analysis. The most recent concentration or value was used when a site was represented by multiple analyses throughout time. Non-oil-field brine data were compiled from sites northeast of the study area near Paradox Valley, Colorado (Rosenbauer and others, 1992, p. 276).

Previous Investigations

The hydrology and geology of Mesozoic-age formations in San Juan County, Utah, and parts of surrounding states have been studied on a regional to local scale by numerous investigators. Waring and Knechtel (1935) presented the first major overview of the general geology and ground-water conditions of southeastern Utah, including the valleys of the San Juan River at Bluff, Utah, and McElmo Creek. A section of the report is devoted to a discussion of artesian conditions. Goode (1958) completed one of the earliest studies of the relation between freshwater aquifers and oil-bearing formations in the Aneth area and suggested that contamination of freshwater zones could take place by surface disposal of salt water or during drilling, producing, and abandonment of oil wells. Barnes (unpub. data, 1959, 36 p.) did a study for Texaco, Inc. to evaluate available sources of water for flooding the oil reservoirs to enhance secondary recovery. This study included pumping tests of the alluvial aquifer along the San Juan River and evaluation of the quality of water from Texaco artesian wells completed in the Entrada, Navajo, and Wingate Sandstones.

Cooley and others (1969) studied the regional hydrogeology of the Navajo and Hopi Indian Reservations in parts of Arizona, New Mexico, and Utah. This

investigation was initiated at the request of the Bureau of Indian Affairs to assess the ground-water resources of reservation land to determine the feasibility of developing ground-water supplies. Sumsion (1975) prepared a report for the U.S. Public Health Service to determine the occurrence and chemical quality of ground water in the Montezuma Creek/Aneth area. The study concluded that potable water supplies could be obtained from aquifers in the Morrison Formation and from alluvium along the San Juan River. Whitfield and others (1983), in a study for the U.S. Department of Energy, estimated water budgets for the ground-water system in the Blanding, Utah, area, about 20 mi north of the Aneth study area, to assess the relations between the freshwater aquifers and the salt strata at depth and the suitability of the salt beds for storage of radioactive wastes.

Avery (1986) studied the movement and chemical quality of ground water and the hydrologic properties of the principal aquifers in eastern San Juan County. Results of the study indicated that water from some wells completed in the Navajo Sandstone in the Aneth area had shown increasing concentrations of dissolved solids since oil-field development and that the possible source of salinity was the Cutler Formation or Hermosa Group (Paradox Formation). Thomas (1989) used data from previous investigations to develop a digital computer model to simulate ground-water movement in the Four Corners area. The model was used to improve the ground-water budget estimate and to better understand vertical flow between the principal aquifers. Howells (1990) mapped the depth to the base of moderately saline (greater than 3,000 mg/L dissolved-solids concentration) ground water in San Juan County and showed that water with dissolved-solids concentrations greater than 10,000 mg/L may be less than 500 ft below land surface, in the Morrison Formation, in some areas in the Greater Aneth Oil Field. Freehey and Cordy (1991) provided an analysis of the hydrogeology of Mesozoic-age formations in the Upper Colorado River Basin, including southeastern Utah, as part of the Regional Aquifer Systems Analysis Program (RASA). The RASA report focused on the horizontal movement of ground water between recharge and discharge areas, vertical movement of water between aquifers, and water quality. Kimball (1992) used hydrochemical characteristics and isotopes to investigate the source of saline water in Mesozoic-age formations. According to this study, which was based on data collected during 1983-84, chemical similarities of water in the Navajo aquifer and in the middle

Paleozoic aquifer (Paradox Formation) suggested that saline water in the Montezuma Creek drainage area in the Greater Aneth Oil Field originated from reinjection of oil-field brine.

Acknowledgments

The authors would like to acknowledge the help of all those who cooperated with or contributed to this study. The authors are particularly grateful for the assistance of both field and office personnel of operators in the Greater Aneth Oil Field and vicinity with regard to locating wells, obtaining well logs, collecting water samples, and providing expertise and resources. These include Texaco Exploration and Production, Inc.; Mobil Exploration and Producing, U.S., Inc.; Phillips Petroleum, Inc.; U.S. Oil and Gas, Inc.; Meridian Oil, Inc.; Von Engineering Company; Raymond T. Duncan, Inc.; and Elkhorn Operating Company. Personnel from these companies are too numerous to list, but without their help, much data would not have been available. Personnel from the Bureau of Land Management and the Utah Division of Oil, Gas, and Mining also helped obtain well-log information. Many people in various Navajo Nation agencies provided input to this study, particularly Michael Johnson of the Navajo Nation Water Resources Management Department, who helped locate well logs and other data from the Navajo water-well data base. Appreciation is extended to the Navajo Tribal Utility Authority for efforts to obtain water samples and to Montezuma Well Service for disposal of saline water. In the U.S. Geological Survey, the authors would like to thank personnel from the field office in Moab, Utah, particularly Michael Hawkins, for efforts in the collection of field data, and Shannon Mahan, Kiyoto Futa, and April Walker in Denver, Colorado, for strontium isotope measurements. Finally, appreciation is extended to the members of the Aneth Technical Committee for support, input, and guidance throughout the study.

DESCRIPTION OF STUDY AREA

The study area includes about 1,200 mi² in the southeastern corner of San Juan County, Utah, and the extreme southwestern corner of Montezuma County, Colorado (fig. 1). The area is part of the Four Corners region where the borders of Colorado, New Mexico, Arizona, and Utah meet at a common point. Most of the area is part of the Navajo Indian Reservation. Part

of the study area in Colorado is in the Ute Mountain Indian Reservation. The Greater Aneth Oil Field covers about 125 mi² in the central part of the study area and is surrounded by numerous smaller oil and gas fields (fig. 1). The largest communities are Montezuma Creek and Aneth, on the Navajo Indian Reservation, and Bluff, on the western edge of the study area. The combined population of these communities is about 1,000 people. The remainder of the study area is sparsely inhabited.

The numbering system for geohydrologic-data sites used in Utah is shown in figure 2. This system locates sites in the study area by township, range, and section. Corresponding map numbers for each of the sites are used in tables within the report.

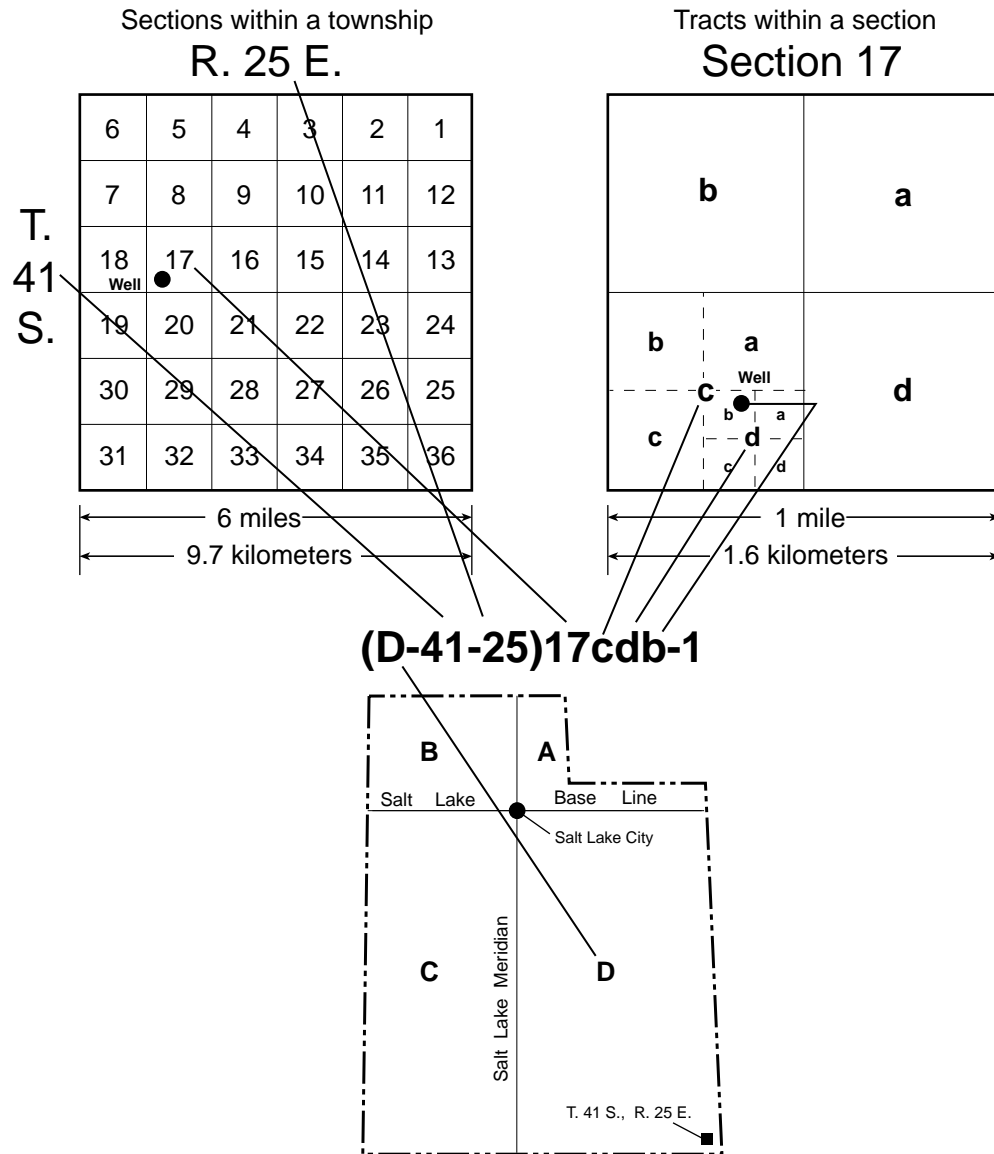
Geographic Setting

The area in the vicinity of the Greater Aneth Oil Field is part of the Colorado Plateau Physiographic Province (Stokes, 1988) and consists of dissected mesas and badland topography that have formed in response to downcutting by the San Juan River and its tributaries. Terraces along much of the San Juan River indicate former levels of the river. The San Juan River flows toward the northwest and west across the middle of the study area and discharges into Lake Powell about 65 mi west of the study area. McElmo Creek is the only entirely perennial tributary to the San Juan River in the study area, flowing generally toward the southwest before discharging into the San Juan River at Aneth (fig. 1). Most drainages north and south of the San Juan River contain ephemeral streams. The lower reach of Montezuma Creek contains the largest ephemeral stream in the study area.

Altitude in the region ranges from about 4,400 ft along the San Juan River to as much as 11,300 ft in the Abajo Mountains, about 35 mi north of the study area. Maximum altitudes in the Sleeping Ute Mountains, about 5 mi east of the study area, in Colorado, and in the Carrizo Mountains, about 10 mi south of the study area, in Arizona, are between 9,500 and 10,000 ft. Broad, flat-topped mesas are present north and south of the San Juan River (fig. 1). Average relief from mesa tops to intervening valleys is generally 400 to 600 ft.

Normal annual precipitation in the study area ranges from about 7 in. south of the San Juan River to 10 in. north of the San Juan River (Avery, 1986, fig. 6, p. 11). Potential average annual evaporation throughout the area substantially exceeds annual precipitation

The system of numbering wells, springs, and other hydrologic-data sites in Utah is based on the cadastral land-survey system of the U.S. Government. The number, in addition to designating the site, describes its position in the land net. The land-survey system divides the State into four quadrants by the Salt Lake Meridian and Base Line. These quadrants are designated by the uppercase letters A, B, C, and D, indicating respectively, the northeast, northwest, southwest, and southeast quadrants. Numbers designating the township and range, in that order, follow the quadrant letter, and the three are enclosed in parentheses. For site locations in southwest Colorado, the parentheses are preceded by the uppercase letter N, indicating the New Mexico Principal Meridian and Base Line. The uppercase letter T preceding the parentheses indicates a half township. The number after the parentheses indicates the section and is followed by three lowercase letters indicating the quarter section, the quarter-quarter section, and the quarter-quarter-quarter section—generally 10 acres for regular sections¹; the lowercase letters a, b, c, and d indicate, respectively, the northeast, northwest, southwest, and southeast quarters of each subdivision. The number after the letters is the serial number of the site within the 10-acre tract. The letter S preceding the serial number denotes a spring. Thus, (D-41-25)17cdb-1 designates the first well constructed or cataloged in the northwest quarter of the southeast quarter of the southwest quarter, section 17, T. 41 S., R. 25 E.



¹Although the basic land unit, the section, is theoretically 1 square mi, many sections are irregular. Such sections are subdivided into 10-acre tracts, generally beginning at the southeast corner, and the surplus or shortage is taken up in the tracts along the north and west sides of the section.

Figure 2. Numbering system for geohydrologic-data sites in Utah.

(Farnsworth and others, 1982, map 3). Annual precipitation along the San Juan River averages about 8 in. and average potential evaporation is about 65 in. Maximum annual precipitation may exceed 30 in. in the adjacent mountains, most of which falls as snow between October and April. Average daytime summer temperatures in the study area reach 90 to 100 °F.

Geologic Setting

Consolidated sedimentary rocks of Jurassic and Cretaceous age crop out in the study area (fig. 3). The largest percentage of outcropping rock consists of the different members of the Jurassic-age Morrison Formation, particularly the Brushy Basin, Westwater Canyon, and Recapture Members (fig. 4). Strata are predominantly sandstone, with intervening beds of siltstone, variegated shale and mudstone, and conglomerate. East of the community of Montezuma Creek, the San Juan River downcuts through the lower part of these shaly units. The basal Bluff Sandstone Member of the Morrison Formation crops out in the southwestern and western parts of the study area, particularly along the San Juan River downstream from its confluence with Montezuma Creek. It is the primary water-bearing unit of the Morrison Formation in the subsurface where it is overlain and confined by other members of the Morrison Formation. Maximum thickness of the Bluff Sandstone is about 350 ft near the community of Bluff. The Cretaceous-age Burro Canyon Formation and Dakota Sandstone cap the Morrison Formation (Brushy Basin Member) on buttes and mesas throughout the study area (figs. 3 and 4).

Quaternary-age alluvial deposits overlie the consolidated rocks in valleys and washes, and eolian deposits locally cover the consolidated rocks on upland areas, particularly in the southwestern parts of the study area. Fine-grained alluvial deposits are present along the floodplain of the San Juan River, and cobbly Quaternary-age deposits cover adjacent terraces. The alluvial deposits are less than 30 ft thick, except along the San Juan River, and generally yield freshwater to wells.

Triassic- to Jurassic-age rocks underlie the study area to a depth of about 2,600 ft and include the principal hydrogeologic units, the Wingate, Navajo, and Entrada Sandstones (fig. 3). The Navajo and Entrada Sandstones crop out only in the extreme southwestern part of the study area. Strata consist primarily of massive beds of eolian sandstone, with interbeds of siltstone and shale. The Kayenta and Carmel Formations

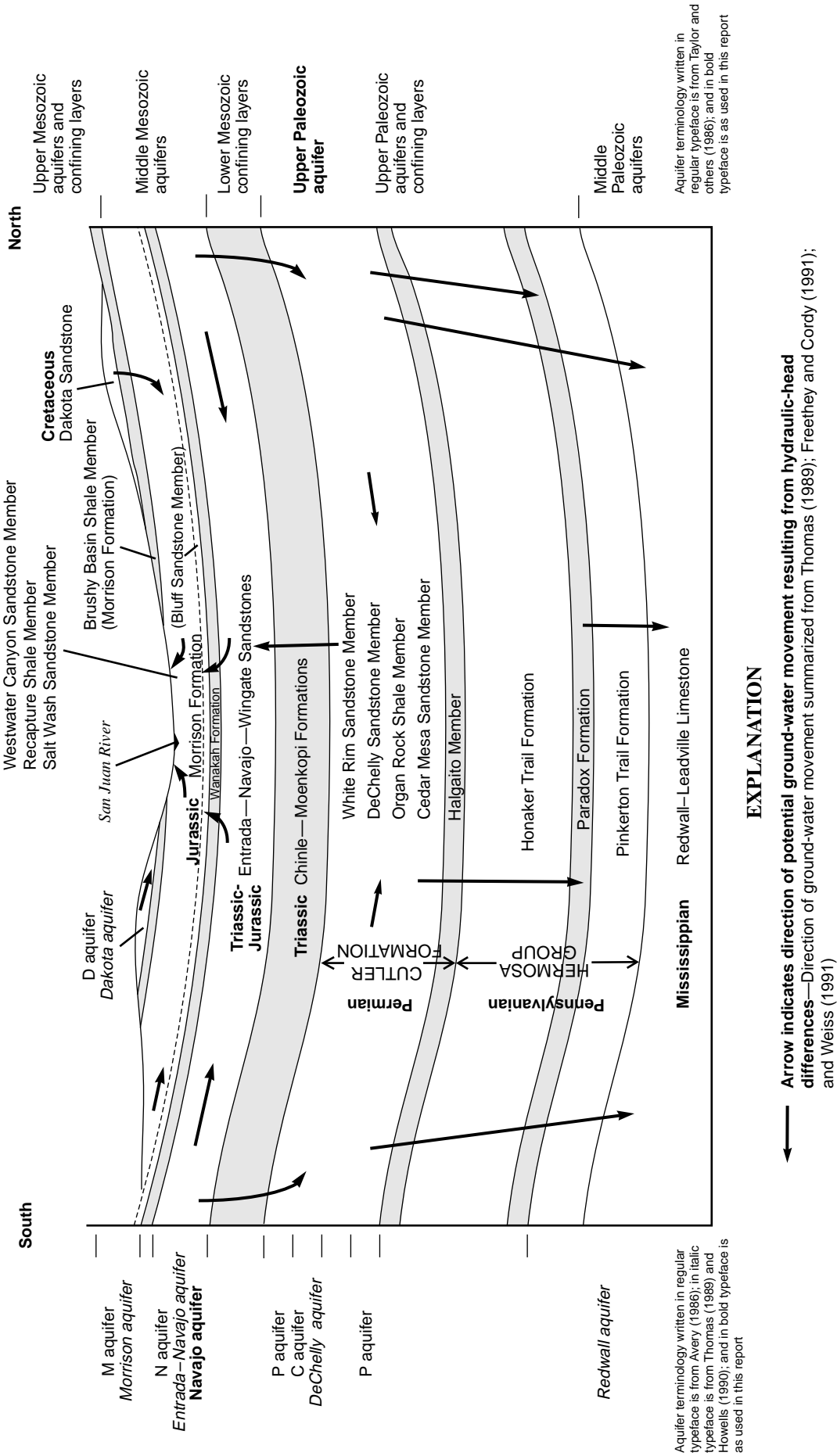
are semiconfining units between the Wingate and Navajo, and the Navajo and Entrada Sandstones, respectively. Average combined thickness of all of these formations in the Aneth area is about 925 ft. The Triassic-age Chinle and Moenkopi Formations underlie the Wingate Sandstone (fig. 3). This massive sequence of shales and siltstones averages about 1,165 ft thick throughout the study area and is the principal confining unit between aquifers in Mesozoic and Paleozoic rocks.

Permian-age rocks of the Cutler Formation, which includes the DeChelly Sandstone Member, underlie the Moenkopi Formation (fig. 3) but generally contain saline water. The Cutler Formation is about 1,950 ft thick in the vicinity of the Greater Aneth Oil Field and thickness of the DeChelly Sandstone ranges from 60 to about 230 ft. To the north of the Greater Aneth Oil Field in T. 38 S., R. 23 and 24 E., and T. 39 S., R. 25 E., water is withdrawn from aquifers in the Cutler Formation and lower part (Shinarump Member) of the Chinle Formation for use in injection operations.

Rocks of the Pennsylvanian-age Hermosa Group underlie the Cutler Formation (fig. 3) and consist of interbedded shale, sandstone, and carbonates (limestone and dolomite), with lesser thicknesses of evaporites (gypsum, anhydrite, and salt). Hydrocarbons are present in carbonate rocks of the Ismay and Desert Creek zones of the Paradox Formation at depths of 5,000 to 6,000 ft below land surface and are the principal oil-bearing units in the Greater Aneth Oil Field and vicinity. The underlying Mississippian-age Leadville Limestone contains only saline water within the study area boundaries.

The study area encompasses the southern part of the west-east trending Blanding Basin, a structural sub-basin of the Paradox Basin (Howells, 1990, fig. 6, p. 12). During the Middle Pennsylvanian Period, the Paradox Basin developed a restricted-circulation hypersaline environment with periodic influxes of normal marine water, which resulted in cyclic deposition of a black shale-carbonate-evaporite sequence (Howells, 1990, p. 24). The deepest part of the Blanding Basin is about 15 mi northeast of Bluff, Utah, and strata generally dip toward the San Juan River from the north and south, at less than 2 degrees (fig. 3).

The Comb Ridge Monocline is a prominent north-trending structural feature west of the study area. Pennsylvanian-age strata that are more than 1 mi deep in the Montezuma Creek/Aneth area are at the surface only 25 mi to the west because of the upwarp. The adjacent Abajo, Sleeping Ute, and Carrizo Mountains, to the north, east, and south of the study area, respec-



AVERAGE DEPTH BELOW LAND SURFACE TO TOP OF HYDROGEOLOGIC UNITS

Morrison Formation—Bluff Sandstone = 265 feet	Cutler Formation = 2,640 feet
Entrada Sandstone = 550 feet	Hermosa Group = 4,585 feet
Navajo Sandstone = 775 feet	Leadville Limestone = 6,910 feet
Chinle Formation = 1,475 feet	

Figure 3. Schematic cross section of hydrogeologic units in the vicinity of the Greater Aneth Oil Field, southeastern San Juan County, Utah.

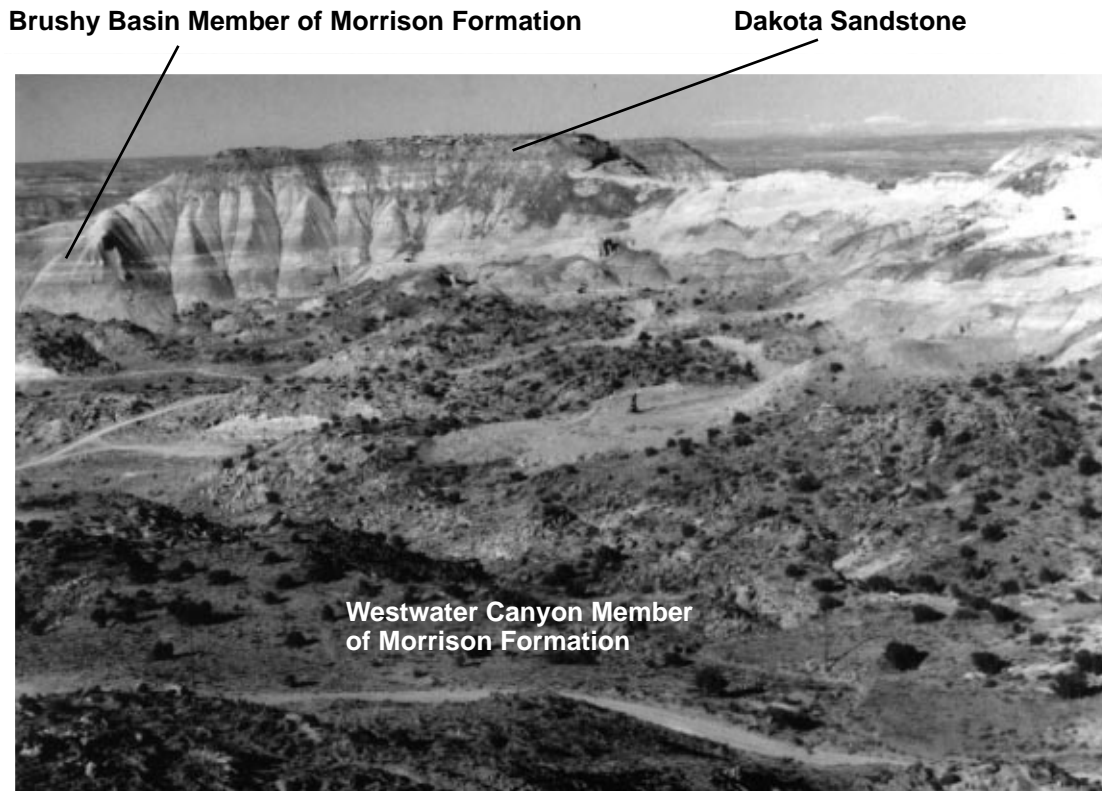


Figure 4. Outcropping strata of the Brushy Basin and Westwater Canyon Members of the Morrison Formation, capped by the Dakota Sandstone, in the Greater Aneth Oil Field, San Juan County, Utah.

tively, consist of igneous rocks that were intruded through overlying strata of Mesozoic age during the Tertiary Period.

History of Oil-Field Development

Drilling began in the Blanding Basin (southern Paradox Basin) in the Aneth area as early as 1930, when a cable-tool test hole flowed oil from the Permian-age DeChelly Sandstone and produced gas from the Pennsylvanian-age Hermosa Group (Smouse, 1993). The first major discovery well, however, was not drilled until 1948 at Boundary Butte (fig. 1), where oil was produced from the Permian-age Coconino Sandstone and the Ismay zone of the Paradox Formation (Hermosa Group) (Clem and Brown, 1984, p. 34). After isolated holes were drilled by Shell Oil Company in the early 1950s, the discovery well at Aneth was drilled by the Texas Company (later Texaco Explora-

tion and Production, Inc.) in February 1956 in T. 40 S., R. 24 E., Sec. 23 (Quigley, 1958, p. 247). This well produced oil from the Ismay and Desert Creek zones of the Paradox Formation from a depth of about 5,850 ft. During 1956 and 1957, the Ratherford, McElmo Creek, and White Mesa Fields also were discovered and recognized as being part of a single large pool; hence, in 1961, all of these fields were combined and included under the name "Greater Aneth Oil Field." Subsequent drilling during the late 1950s increased the proven acreage of the Greater Aneth Oil Field and resulted in the discovery of numerous satellite oil fields, including South Ismay-Flodine Park (1956), Recapture Creek (1956), Bluff (1956), Gothic Mesa (1957), and Tohonadla (1957) (Clem and Brown, 1984)(fig. 1). Additional operators that were active in the early exploration and discovery of these and other fields included Carter, Sun, Gulf, Pure, Superior, and Continental Oil Companies (Moore and Hawks, 1993). The principal operators in the Greater Aneth Oil Field currently

(1995) are Texaco Exploration and Production, Inc. (Aneth Unit); Mobil Exploration and Producing, U.S., Inc. (McElmo Creek and Ratherford Units); and U.S. Oil and Gas, Inc. (White Mesa Unit).

Shortly after the major discoveries in the late 1950s, field pressures decreased and water injection was necessary to increase productivity; consequently, beginning in 1961, secondary recovery operations began (Moore and Hawks, 1993). Because the volume of water needed for injection purposes exceeded the volume of water produced with the oil, numerous shallow water wells were drilled into the alluvium along the floodplain of the San Juan River to provide the necessary "make-up" water. From 1984 to 1991, about 316 million barrels of water from the alluvium and "produced" (formation) water from oil wells, were injected back into the Paradox Formation, although yearly injection rates have declined substantially (Daniel Jarvis, Utah Division of Oil, Gas, and Mining, written commun., 1991). Water from the alluvium is mixed or "comingled" with produced water prior to injection, or alternately injected with the produced water. Injection of produced water takes place through wells drilled specifically for injection back into the oil-producing formations or by using wells that have been converted from previously producing oil wells or dry holes. In recent years, carbon dioxide also has been used to increase field pressures and enhance oil and gas recovery in parts of the Greater Aneth Oil Field (Moore and Hawks, 1993).

Producing oil strata in the Greater Aneth Oil Field and vicinity are primarily in carbonate units of the Pennsylvanian-age Paradox Formation (Ismay and Desert Creek zones) at depths generally ranging from 5,000 to 6,000 ft. Producing intervals within these zones average 40 to 50 ft thick but vary in thickness in the Greater Aneth Oil Field and between fields (Moore and Hawks, 1993). The reservoir lithologies consist of oolitic and fossiliferous (algal) limestones and dolomites that have formed bioherms and bioclastic mounds up to 200 ft thick (Clem and Brown, 1984, p. 18). Minor amounts of oil and gas also have been obtained from the Mississippian-age Leadville Limestone. The Greater Aneth Oil Field contains more than 48,000 acres of proven reserves, with about 450 producing oil wells on a 40-acre spacing (Moore and Hawks, 1993). Total cumulative production from primary and secondary recovery as of 1992 is estimated to be about 310 million barrels of oil, 336 million cubic feet of gas, and more than 400 million barrels of water (Clem and Brown, 1984, p. 18; and Moore and Hawks, 1993).

Water Use in the Study Area

The existence of artesian ground-water conditions in southeastern Utah was recognized as early as 1908 during drilling of scattered oil-test wells (Lofgren, 1954, p. 107). Artesian conditions, characterized by hydraulic pressure greater than atmospheric pressure, also existed in wells drilled in Bluff, Utah, in 1909, at depths of 800 to 1,100 ft. These wells yielded water from the Navajo and Wingate Sandstones for domestic and irrigation use. Water in these sandstones was under sufficient hydraulic pressure to discharge at land surface. Two of the earliest wells to yield freshwater in the study area are located northeast of Hatch Trading Post in T. 39 S., R. 25 E., Sec. 5 (fig. 1). Drilled in September 1951, these wells indicated that an untapped source of water in the Entrada, Navajo, and Wingate Sandstones was present in this area.

After the discovery of the Aneth Oil Field in 1956, a number of water wells were drilled to provide water for oil-drilling operations and to provide a source of "relatively" freshwater (dissolved-solids concentrations less than 10,000 mg/L) to mix with produced (formation) water for injection purposes. Most of these wells yielded water from the Entrada, Navajo, and Wingate Sandstones (Barnes, unpub. data, table 3, p. 18). After 1961, however, these bedrock wells could not provide the volume of water necessary for oil-field operations, and numerous shallow wells subsequently were drilled in the floodplain of the San Juan River between Aneth and Montezuma Creek. The volume of water withdrawn from wells in alluvium along the San Juan River for use in injection operations in the Aneth, Ratherford, and McElmo Creek Units from 1962-90 has ranged from a maximum of about 12 acre-ft/d during 1963-67 to about 2.8 acre-ft/d during 1988-90 (James Vanderhill, Mobil Exploration and Producing, U.S., Inc., written commun., 1994). Generally, the volume of required make-up water from the San Juan River has decreased through time because a larger volume of produced water has been pumped relative to the volume of oil, and because of recent carbon dioxide injection. Most of the water wells in bedrock aquifers that were drilled originally for oil-field operations have been plugged and abandoned or given to the Navajo Nation for domestic and stock use. Some oil-test holes (dry holes or previously producing oil wells) also have been plugged back to water-bearing formations and converted to water wells. Water that discharges from converted oil-test holes and water wells generally is artesian and saline. The volume of water yielded from

flowing artesian wells in the study area varies substantially and is not monitored. Measured discharge from individual flowing wells during the study, however, ranged from less than 1 to about 150 gal/min.

Most water used for domestic and stock purposes outside of communities on the Navajo Indian Reservation is withdrawn by wells powered by windmills (fig. 5). Windmills were constructed beginning in the 1940s to provide power to pump freshwater for families who lived far from communities where freshwater was available. Depending on location and depth, wells equipped with windmills yield water from the Dakota Sandstone, the Morrison Formation (including the Bluff Sandstone Member), and the Entrada, Navajo, and Wingate Sandstones. Generally, windmills pump less than 5 gal/min of water and operate intermittently. The volume of water pumped by windmills from bed-rock aquifers is not monitored and thus is unknown (Michael Johnson, Navajo Water Resources Management Department, oral commun., 1994). Although most water pumped by windmills is fresh (dissolved-solids concentration less than 1,000 mg/L), the water is not approved by Navajo regulatory agencies for drinking-water use; hence, families in outlying areas must haul water from approved wells. An additional source of freshwater for outlying areas is derived from wells equipped with hand pumps (fig. 6). These wells generally are located in washes and yield water from alluvial deposits at shallow depths. The volume of water yielded by hand pumps is also unknown but is relatively small compared with yields from other sources in the study area.

Drinking-water supplies for the communities of Bluff, Montezuma Creek, and Aneth are obtained from wells. Water from public-supply wells in Bluff is derived from the Wingate and Navajo Sandstones. In 1981, pumpage from municipal wells in Bluff was about 34.1 acre-ft (Hooper and Schwarting, 1982, p. 55). Water from three public-supply wells in Montezuma Creek is pumped from the Bluff and Entrada Sandstones. Average usage from these three wells for the period January 1990 to January 1995 was about 94 acre-ft/yr. Drinking water for Aneth is pumped from two deep wells completed in the Bluff Sandstone about 6 mi north of Aneth and then piped to the community for distribution. Average usage from both wells from January 1990 to January 1995 was about 82 acre-ft/yr. In addition, water from two wells completed in the Navajo Sandstone between the communities of Bluff and Montezuma Creek is used in natural gas operations by Elkhorn Operating Company. During the 1991-92

and 1994 calendar years, withdrawal from these wells averaged about 138 acre-ft/yr (Gene Gruette, Elkhorn Operating Company, written commun., 1995).

HYDROLOGIC SETTING

The hydrologic system in the vicinity of the Greater Aneth Oil Field consists of Paleozoic and Mesozoic rocks that contain sandstone aquifers and interbedded shaly confining units (fig. 3). The San Juan River is the principal discharge area for the aquifers in rocks of Mesozoic age in the study area. The stratigraphy and associated hydrologic units of San Juan County, including the Aneth area, have been described by Avery (1986) and Howells (1990).

Surface Water

The San Juan River is the principal base-level stream in the study area, into which all surface drainage flows either directly or indirectly (fig. 1). Discharge of the San Juan River has been regulated at Navajo Reservoir in northwestern New Mexico since 1962; hence, river discharge is substantially influenced by reservoir releases, which depend on precipitation in the drainage basin. Records of stream discharge from the U.S. Geological Survey streamflow-gaging station at Mexican Hat, Utah, about 20 mi west of the study area, indicate that the mean daily discharge for the 1992-94 water years ranged from 528 ft³/s (August 1994) to 7,123 ft³/s (June 1993) (ReMillard and others, 1993, 1994, and 1995). Stream discharge also is influenced by inflow from McElmo Creek, snowmelt and thunderstorm runoff, withdrawals from the river for irrigation and industrial use, and losses from evapotranspiration.

The only perennial tributary to the San Juan River in the study area is McElmo Creek (fig. 1). McElmo Creek has its headwaters in Colorado but discharges into the San Juan River at Aneth. Records of stream discharge from the U.S. Geological Survey streamflow-gaging station at Aneth indicate that mean daily discharge for water year 1982, the last period of record, ranged from 23.4 ft³/s to 211 ft³/s (ReMillard and others, 1983, p. 230). Discharge of McElmo Creek is influenced by irrigation return flows that contribute to peak flows in late summer (Avery, 1986, p. 17) that likely prevent McElmo Creek from being an ephemeral stream in its lower reaches.

Most of the study area is drained by ephemeral streams. The largest ephemeral streams are Monte-



Figure 5. Navajo Nation windmill and holding tank near the Greater Aneth Oil Field, San Juan County, Utah.

zuma, Recapture, and Desert Creeks (fig. 1). Headwaters of Montezuma and Recapture Creeks are in the Abajo Mountains, about 35 mi north of the study area. Although the creeks are perennial in the upper reaches, evapotranspiration, irrigation diversions, and channel losses, particularly during the summer, generally reduce flows to zero before they discharge into the San Juan River. However, surface water that is lost in the downstream reaches of many washes, particularly near the San Juan River, is presumed to move downgradient through alluvial materials and discharge indirectly to

the river. Streamflow is generally present throughout the entire reaches of Montezuma Creek and Recapture Creek only during snowmelt runoff and locally intense summer thunderstorms. Records of discharge from the U.S. Geological Survey streamflow-gaging station 5 mi north of the community of Montezuma Creek indicate that in the downstream reaches of Montezuma Creek, stream discharge can exceed $500 \text{ ft}^3/\text{s}$ in the spring following snowmelt but decrease to zero flow by summer (ReMillard and others, 1988, p. 151).



Figure 6. Hand-pump water well in alluvial deposits near Montezuma Creek in the Greater Aneth Oil Field, San Juan County, Utah.

Ground Water

The ground-water system in the vicinity of the Greater Aneth Oil Field consists of a sequence of bed-rock aquifers and confining units that are locally overlain by aquifers in unconsolidated deposits (fig. 3). Alluvial aquifers are present in tributary drainages that contain ephemeral streams and along the San Juan River floodplain. Although aquifers in alluvium are limited in size and thickness, they generally contain a substantial volume of freshwater. The principal bed-rock aquifers in rocks of Mesozoic age include those in the Cretaceous Dakota Sandstone, Jurassic Morrison Formation (including the Bluff Sandstone Member), and the Entrada, Navajo, and Wingate Sandstones (fig. 3). Generally, aquifers in the Bluff, Entrada, Navajo, and Wingate Sandstones are confined in this area, and

water flows from wells because the potentiometric surface of the water in the aquifers is above land surface.

The Burro Canyon Formation and the Dakota Sandstone are part of the Dakota aquifer (Thomas, 1989, and Howells, 1990) or the “D” aquifer of Avery (1986) (fig. 3). Recharge and discharge from the Dakota aquifer is localized because of the discontinuous erosional remnants of the formation. Discharge from the Dakota aquifer is from springs along the contact between the Dakota Sandstone and the underlying Brushy Basin Member of the Morrison Formation, from wells on higher mesas, and by evapotranspiration. Thickness of the Dakota aquifer in the study area is generally less than 100 ft.

The Westwater Canyon, Recapture, Salt Wash, and Bluff Sandstone Members of the Morrison Formation are included in the Morrison aquifer (Thomas, 1989, and Howells, 1990), which correlates with the “M” aquifer of Avery (1986) (fig. 3). The Brushy Basin

Member of the Morrison Formation is the confining unit between the “D” and “M” aquifers. The Entrada Sandstone, sandstone members of the Morrison Formation, and the Dakota Sandstone are included in the D multiple-aquifer system of Cooley and others (1969). Whitfield and others (1983) considered the Bluff Sandstone to be a separate formation and part of the Mesozoic Sandstone aquifer. Because the Dakota and Morrison Formations crop out in the vicinity of the Greater Aneth Oil Field, the aquifers in these units are generally unconfined (water-table conditions). In the western part of the study area, where the Bluff Sandstone Member crops out, the aquifer is unconfined, but where the unit is overlain by other shaly members of the Morrison Formation, the aquifer may be confined (artesian conditions).

Recharge to the unconfined aquifers, including alluvial deposits; the Dakota Sandstone; and the Westwater Canyon, Recapture, Salt Wash, and Bluff Sandstone Members of the Morrison Formation, takes place primarily by direct infiltration of precipitation on outcrop areas and by infiltration of surface water along washes, such as Montezuma Creek. During 1982-83, Avery (1986, table 3, p. 70) measured a discharge of 3.1 ft³/s in Montezuma Creek in T. 36 S., R. 24 E., Sec. 35, just north of the study area, but no flow was present in the channel about 6 mi downstream. Discharge from the Morrison aquifer is from springs, outflow to streams, evapotranspiration, and from wells. Evapotranspiration takes place where phreatophytes are present and the water table is relatively close to the surface, particularly along washes. On the basis of base-flow data from 1982 to 1983, Avery (1986, p. 40) estimated that McElmo Creek gained 1,500 acre-ft/yr (2.1 ft³/s) from the Morrison aquifer between the Colorado/Utah State line and the mouth of the creek at the San Juan River. Regional ground-water movement in the Morrison aquifer, below the Brushy Basin Member, is toward the San Juan River. Springs that discharge from Morrison Formation sandstones where they crop out along the San Juan River valley also indicate that the San Juan River is the primary discharge area for the unconfined Morrison aquifer. Thickness of the Morrison aquifer is as much as 400 ft in some areas near the Utah/Arizona State line.

The Entrada, Navajo, and Wingate Sandstones, along with the intervening semiconfining units, the Carmel Formation and the Kayenta Formation, are included in the Entrada-Navajo aquifer of Thomas (1989) and Howells (1990). Taylor and others (1986) included these formations along with the overlying

sandstone members of the Morrison Formation in the middle Mesozoic aquifers (fig. 3). Whitfield and others (1983) included these formations along with the Morrison Formation and the Dakota Sandstone as part of the Mesozoic Sandstone aquifer. The Entrada-Navajo aquifer correlates with the “N” aquifer of Avery (1986). The Wanakah Formation is the confining unit between the “M” and “N” aquifers (fig. 3). Cooley and others (1969) defined the N multiple-aquifer system to include the Navajo Sandstone, sandy lithologies of the Kayenta Formation, and the Wingate Sandstone. In this report, the Entrada-Navajo aquifer is referred to as the Navajo aquifer. Barnes (unpub. data, 1959, p. 16) also used the term Navajo aquifer to include the Entrada, Navajo, and Wingate Sandstones. The Navajo aquifer is the principal aquifer from which water is withdrawn in the study area both north and south of the San Juan River and is discussed in more detail in the following sections.

The “P” aquifer of Avery (1986) includes permeable units in the Cutler Formation, particularly the Cedar Mesa Sandstone Member. The Chinle and Moenkopi Formations are the thick confining units between the “N” and “P” aquifers (fig. 3). Whitfield and others (1983) defined the Cutler Formation as the Cutler aquifer. Howells (1990) also included the Rico Formation and part of the Honaker Trail Formation as part of the Cutler aquifer. The “C” aquifer of Avery (1986) is the saturated part of the DeChelly Sandstone Member of the Cutler Formation and is equivalent to the DeChelly aquifer of Howells (1990). The C multiple-aquifer system of Cooley and others (1969) includes the White Rim and DeChelly Sandstone Members, and the overlying Shinarump Member of the Chinle Formation. In this report, the permeable sandstones of the Cutler Formation, particularly the DeChelly Sandstone, are included in the upper Paleozoic aquifer, partly following the usage of Taylor and others (1986) (fig. 3), along with the lower Mesozoic Shinarump Member of the Chinle Formation.

The Navajo Aquifer

The physical boundaries of the Navajo aquifer correspond to the physical limits of the Entrada, Navajo, and Wingate Sandstones in most of the study area because the formations that contain the aquifers are generally fully saturated where overlain by the Morrison Formation. Where these formations crop out in the southwestern part of the study area or are at shallow depths beneath the land surface, the formations are

only partly saturated. The Navajo aquifer generally ranges from 750 to 1,000 ft in thickness in the vicinity of the Greater Aneth Oil Field, with the top of the aquifer (top of Entrada Sandstone) averaging 550 ft below land surface (fig. 3).

Recharge

The Navajo aquifer is recharged primarily by infiltration of precipitation on and along the flanks of the Abajo Mountains to the north of the study area (fig. 7), Sleeping Ute Mountain and possibly other mountains to the east, in Colorado, and the Carrizo Mountains to the south, in Arizona (Avery, 1986, p. 28; Thomas, 1989, p. 37; and Howells, 1990, p. 28). Because of the altitude, amount of precipitation, and relation to the surrounding sedimentary rocks, these mountains are likely the source of recharge for most of the aquifers in the study area and the headwater areas for most tributary streams to the San Juan River. In addition, because the igneous rocks at the core of these mountains were intruded into the overlying sedimentary rocks, strata along the flanks generally dip away from the mountains and have been intensely fractured. As a result, Cooley and others (1969, p. 41) thought that the shattered sedimentary rocks around the margins of the Carrizo Mountains would enhance recharge to the Navajo aquifer through interformational movement of water. Extensive areas of the Wingate Sandstone crop out along the southern part of the Carrizo Mountains and also could provide a substantial source of recharge to the Navajo aquifer (Strobell, 1956). In addition, recharge to the Navajo aquifer may take place by potential upward movement of water through underlying formations, as discussed in subsequent sections of this report.

Most precipitation takes place above 8,000 ft in the Abajo Mountains and above 7,000 ft in the Sleeping Ute and Carrizo Mountains. Recharge to the bedrock aquifers from the mountains is estimated to be about 5 to 15 percent of the mean annual precipitation for these areas, compared with an estimated 1 to 3 percent of the mean annual precipitation in the semi-arid plateau areas below these altitudes (Thomas, 1989, p. 37); thus, ground-water recharge in these mountains is estimated to range from 8,000 to 25,000 acre-ft/yr or 11 to 34 ft³/s.

On the basis of relative recharge altitudes and sources, projected hydrologic flow paths determined from potentiometric contours, and isotope data presented in subsequent sections of this report, ground-

water movement in the Navajo aquifer was separated into two distinct areas (fig. 8). Primary recharge areas along the flanks of the Abajo Mountains and possibly mountain ranges to the northeast in Colorado are high-altitude sources (greater than 10,000 ft) and were designated as area 1. Primary recharge areas along the flanks of the Sleeping Ute and Carrizo Mountains are relatively low-altitude sources (less than 10,000 ft) and were designated as area 2. Wells completed in the Navajo aquifer north of McElmo Creek and north of the San Juan River downstream from its confluence with McElmo Creek are included in area 1. Wells completed in the Navajo aquifer south and east of McElmo Creek and south of the San Juan River are included in area 2.

Recharge to the unconfined parts of the Navajo aquifer takes place only in the southwestern part of the study area where the Entrada and Navajo Sandstones crop out, particularly where they are covered by alluvial and eolian deposits. Recharge to the Navajo aquifer also likely takes place over large outcrop areas in upper Chinle Creek south and west of the study area, in Arizona, and moves toward the San Juan River (Avery, 1986, p. 28). Although infiltration of precipitation takes place throughout extensive outcrop areas at lower altitudes, annual precipitation rates are very low, average temperatures are considerably warmer, and evapotranspiration rates are high; hence, recharge to the ground-water system is small compared with recharge that takes place in the mountain areas.

Discharge

Water levels in the Navajo aquifer indicate that ground water moves from mountainous recharge areas in the north, east, and south toward the study area and discharges into the San Juan River (fig. 8). Ground-water movement between recharge and discharge areas appears to be controlled by geologic structure and stratigraphy (Howells, 1990, p. 27) and probably takes place along primary (intergranular, bedding plane, cross-bed) and secondary (fracture) pathways. Ground water probably moves down-dip toward the San Juan River in much of the area because the river flows generally east to west across the Blanding Basin and the strata dip toward the river valley from the north and south. In addition, increasing hydraulic head with depth (resulting in artesian conditions) and measured gains in river discharge indicate that the San Juan River is a discharge area for the Navajo aquifer. Water from the Navajo aquifer moves upward into the Morrison aquifer before discharging into the San Juan River



Figure 7. Abajo Mountains near Monticello, Utah, about 35 miles north of the study area, San Juan County, Utah

because the Entrada, Navajo, and Wingate Sandstones do not crop out along the San Juan River in the study area (fig. 3). Water from the Navajo aquifer also may discharge upward through the Morrison Formation to McElmo Creek before discharging into the San Juan River (fig. 8).

Using estimated values of hydraulic conductivity, hydraulic gradient, and cross-sectional area, Avery (1986, p. 31) estimated that $6.9 \text{ ft}^3/\text{s}$ was discharging from the Navajo aquifer to the San Juan River in a 17.5 mi reach upstream from the Comb Ridge Monocline, west of the study area. Avery (1986, p. 18) also used discharge records from U.S. Geological Survey stream-flow-gaging stations on the San Juan River at Four Corners, Colorado, the San Juan River at Mexican Hat, Utah, about 20 mi downstream from Bluff, and McElmo Creek at Aneth, for November 1980, to show that net gain of the San Juan River from bedrock aquifers

was about $66 \text{ ft}^3/\text{s}$. In February 1982, calculated gain between these gaging stations was about $200 \text{ ft}^3/\text{s}$ (ReMillard and others, 1983). During this time of year, change in discharge of the river is small, evapotranspiration is minimal, and base flow is assumed to be attributed to ground-water inflow. Whitfield and others (1983, p. 43) estimated base flow to the San Juan River from the Mesozoic aquifer system in July 1959, before construction of Navajo Dam, to be about $28.6 \text{ ft}^3/\text{s}$ between Shiprock, New Mexico, about 40 mi upstream from Aneth, and Mexican Hat, Utah.

Water also discharges from the Navajo aquifer from flowing artesian wells and wells that are pumped, particularly by windmills. Water discharges from the open bores of water wells (fig. 9) and dry holes and previously producing oil wells that were plugged back to water-bearing formations. Water discharges from the annulus between the surface and intermediate casings

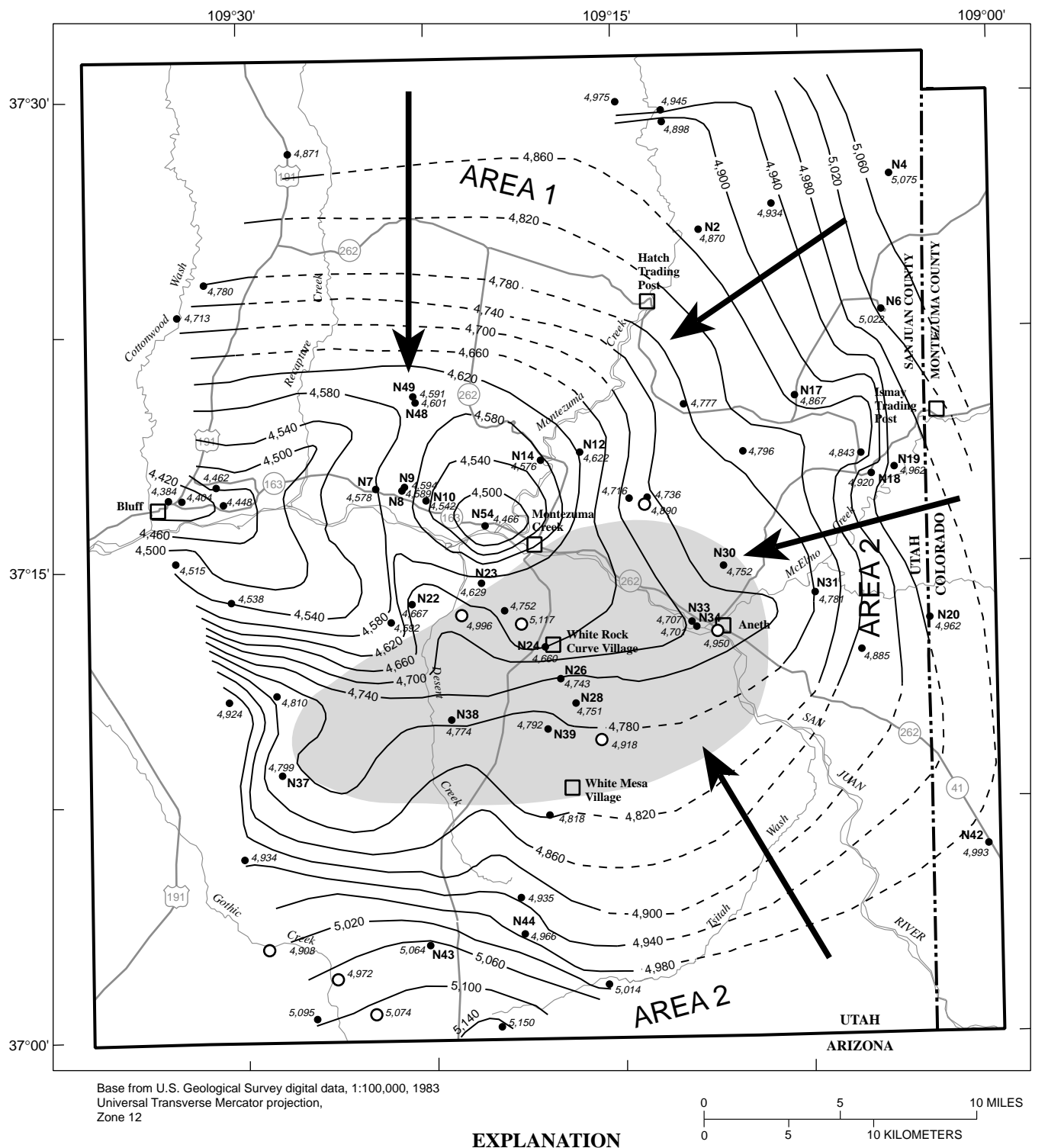


Figure 8. Generalized potentiometric surface of the Navajo aquifer, directions of ground-water movement, and area where hydraulic head in upper Paleozoic aquifer is higher than that in Navajo aquifer, southeastern San Juan County, Utah.

of some producing and plugged and abandoned oil wells. Water also discharges from around the outside of casings (between the surface casing and borehole walls) of some water wells and plugged and abandoned oil wells, and from around a few plugged and abandoned oil-well markers. Water that discharges from and around these wells generally flows onto the ground and into nearby washes where it infiltrates into the alluvial deposits. Some of this water likely infiltrates through the alluvium and into the underlying Morrison aquifer. Locations of 56 selected wells in the Navajo aquifer and other wells, springs, and sites in the study area are shown in figure 10. Data for springs and selected wells completed in the Navajo, alluvial, Dakota, Morrison, and upper Paleozoic aquifers are presented in table 1.

Estimates and measurements of discharge from individual flowing wells ranged from less than 1 to as much as 150 gal/min during the study (table 1). Generally, discharge did not vary for an individual well and observed variations in discharge from some wells were the result of controlled free-flow. Differences in discharge from well to well are attributed to differences in well depth, perforated interval, hydraulic head, and hydraulic conductivity of the aquifer in the yielding formation. On the basis of measured and estimated discharge of 30 free-flowing and "leaking" wells, water discharged from the Navajo aquifer at the rate of about 375 gal/min (600 acre-ft/yr) in 1992 and 1993. Combined discharge from wells N35 and N46 was almost 100 gal/min and was sufficient to enable water to flow on the surface directly to the San Juan River. Prior to 1989, when the study and estimates of discharge were begun, discharge from flowing wells was monitored only intermittently and discharge from individual wells may have been variable. In addition, flows have likely decreased during the time since the wells were constructed, particularly in the early years (Lofgren, 1954, p. 115). Beginning in 1992, selected flowing wells in the Greater Aneth Oil Field and vicinity were plugged, reducing the volume of water being discharged by about 10 to 12 percent.

The contributing formation yielding water to many flowing wells cannot be determined accurately, particularly for wells that were not drilled for water withdrawal purposes or that discharge water by avenues other than through the wellbore. Discussions with oil-field personnel, "Report of Water Encountered During Drilling" (Utah Division of Water Rights, unpub. data), and information derived from oil-well logs indicate that water under artesian pressure probably dis-

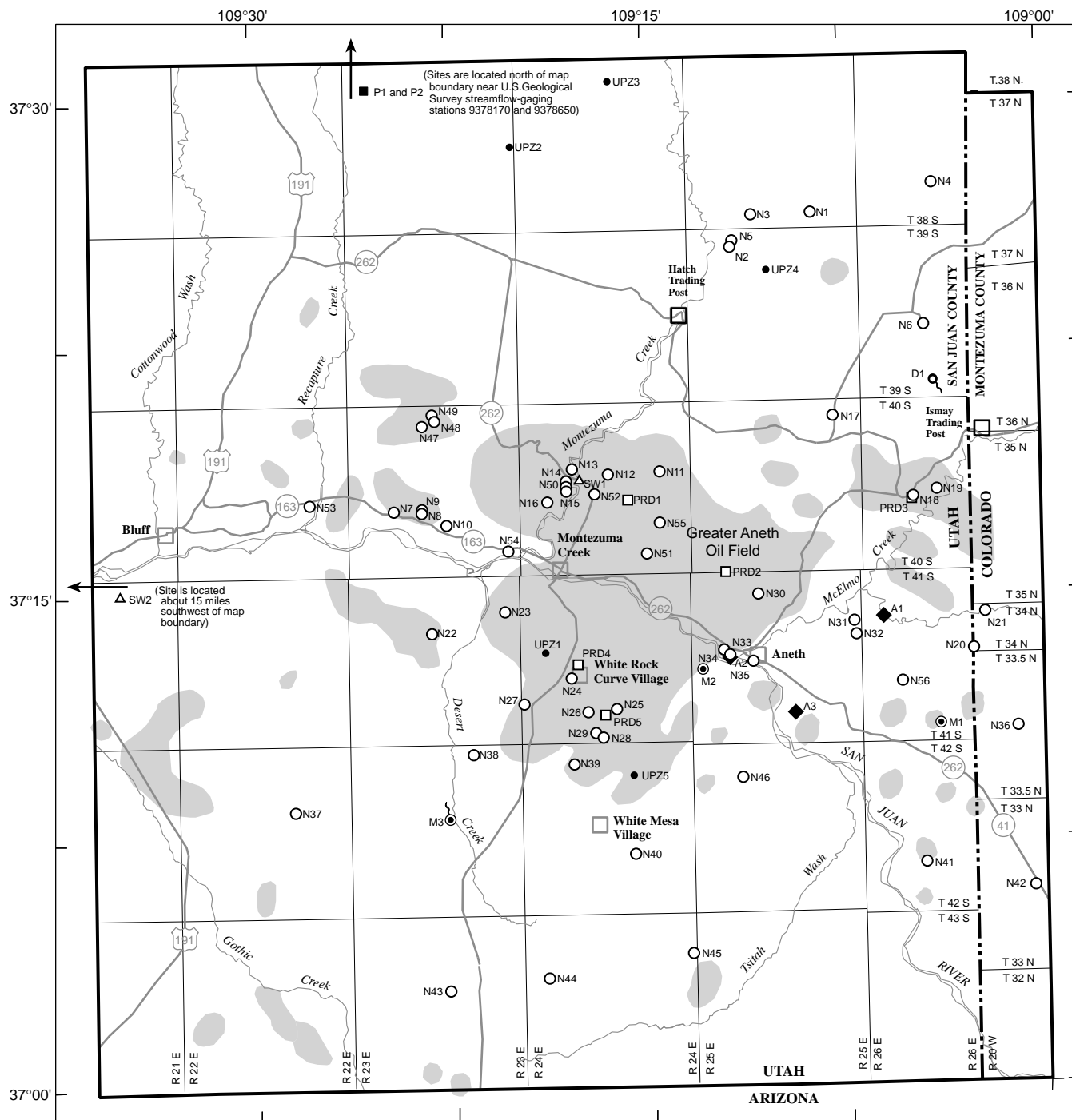
charges from stratigraphic units below the Salt Wash Member of the Morrison Formation (fig. 3) in most wells. Many of these wells were perforated in multiple intervals and may yield water from one or all of the formations of the Navajo aquifer. Some wells that yield water from the upper part of the Navajo aquifer (Entrada Sandstone) may also yield water from the overlying Bluff Sandstone Member of the Morrison Formation. In wells where stratigraphic units below the base of the Navajo aquifer are perforated or otherwise open to the wellbore, water also might originate from other aquifers (James Walker, Navajo Nation Environmental Protection Agency, written commun., 1995). Water from most Texaco supply wells discharges from all three sandstones (Entrada, Navajo, and Wingate) of the Navajo aquifer (Larry Schlotterback, Texaco Exploration and Production, Inc., written commun., 1994). Relative percentages of water from individual formations in the wells, however, generally cannot be determined.

Water-Level Declines

Water levels (hydraulic heads) have declined in many wells in the Aneth area since the early 1900s. Lofgren (1954, p. 117) noted that water levels in Bluff city municipal wells had declined from more than 150 ft above land surface in 1909 to only 80 ft by 1954. Barnes (unpub. data, 1959, p. 15) also stated that the altitude of the potentiometric surface in the Navajo aquifer in T. 40 S., R. 24 E. was 4,830 ft, a minimum of 100 ft higher than the altitude of the potentiometric surface determined from water-level measurements in Navajo aquifer wells in this area during the study. Water-level declines can be caused by pumping or long-term discharge from wells that flow freely at land surface. Water level in a well in T. 41 S., R. 24 E., Sec. 18 declined from 200 ft below land surface in 1956, 6 days after the well was drilled, to 378 ft below land surface in 1994, a decline of 178 ft during 38 years. Because this well had not been pumped for at least 15 years, the decline may have taken place in less than 20 years; however, the apparent decline also might have been a result of effects from other wells in the vicinity. Water level in well N6 declined from 113 ft below land surface in 1963 when the well was drilled, to 205 ft below land surface in 1981, to 217.5 ft below land surface in 1993, a decline of more than 104 ft during 30 years (table 1). This well has been in service since 1963 and no other wells are present in this area that would



Figure 9. Flowing water wells N30 (top) and N16 (bottom) in the Greater Aneth Oil Field, San Juan County, Utah.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection,
Zone 12

EXPLANATION

Area of oil field

Boundary of study area

Sites—Number is site identification number

N43 ○ Well completed in Navajo aquifer

M1 ● Well completed in Morrison aquifer

M3 ○ Spring discharging from Morrison aquifer

A3 ◆ Well completed in alluvial aquifer

D1 ○ Spring discharging from Dakota aquifer

UP25 ● Well completed in upper Paleozoic aquifer

SW1 △ Surface-water gaging site

P1 ■ Precipitation site

PRD5 □ Brine-injection facility

Figure 10. Location of selected wells, springs, surface-water sites, precipitation sites, and brine-injection facilities in and near the Greater Aneth Oil Field, San Juan County, Utah.

affect water levels; thus, the observed decline probably is the result of withdrawals from only this well.

The prominent closed depression in the potentiometric surface near Montezuma Creek may be the result of pumping from one or more wells in this area (fig. 8). For example, well N10 is capable of discharging an estimated 48 gal/min, and the altitude of the potentiometric surface at this well is about 50 ft lower than the altitude of the potentiometric surface at wells N8 and N9 immediately to the west. Pumping from well N54, at the center of the area of drawdown, also might contribute to the lowering of the potentiometric surface in this area. The potentiometric low could have been affected by pumping of municipal wells in Montezuma Creek that withdraw water from the Bluff and Entrada Sandstones, or by historic pumping of wells for industrial use south of Montezuma Creek (Avery, 1986, p. 32). Water-level declines around other flowing wells in the Aneth area also have likely taken place, but lowering of the potentiometric surface may not be obvious because of the large distance between wells (fig. 8). In addition, inaccuracies in the potentiometric surface are inherent because the water-level altitudes determined from hydraulic-head data are from wells of different depths in the Navajo aquifer, and hydraulic head is variable with depth.

Discharge from wells also has declined with decreasing water levels. Well N10 had a water level of about 74 ft above land surface and discharged 87 gal/min in 1983, but the water level had dropped to about 42 ft above land surface and discharge decreased to 48 gal/min when measured in 1992-94 (table 1). Initially, new flowing wells in the Montezuma Creek area yielded as much as 500 gal/min and had water levels exceeding 300 ft above land surface; within a month, however, these wells generally discharged less than 100 gal/min and had considerably lower water levels, indicating low hydraulic conductivity (low permeability) of the aquifer (Lofgren, 1954, p. 115).

Water withdrawals for domestic, irrigation, and industrial use in the Aneth area are probably not the cause of the observed water-level declines in some areas because most water withdrawn for these purposes is derived from shallower aquifers (such as the Bluff Sandstone) that overlie the Navajo aquifer and are separated from the Navajo by confining units. As previously noted, however, many flowing wells in the Aneth area have discharged water from the Navajo aquifer intermittently since the late 1950s and early 1960s. If these wells are assumed to have been flowing unabated for only half of the time since they were drilled (an

average of 15 years), at a rate similar to that measured or estimated during this study (1992-93), about 300 acre-ft/yr, or as much as 4,500 acre-ft, could have been discharged from the Navajo aquifer. Withdrawals from the Navajo aquifer from pumped wells, particularly N8, N9, and N21, are an additional several hundred acre-ft/yr, and water-level declines would be expected.

Potential for Vertical Movement

The potential for upward movement of water from the Navajo aquifer into the overlying Morrison aquifer is a function of the difference in water levels or hydraulic heads between the two aquifers (Thomas, 1989, p. 20). Where hydraulic head in the Navajo aquifer is higher than hydraulic head in the Morrison aquifer, water from the Navajo aquifer may move upward into the Morrison aquifer. Hydraulic head in the Navajo aquifer is higher than that in overlying aquifers in an area about 10 to 15 mi wide on either side of the San Juan River (Avery, 1986, fig. 14, p. 27). Farther from the river, outside of this area, the hydraulic gradient is downward from the Morrison aquifer to the Navajo aquifer. Depth to the Navajo aquifer increases away from the river, and altitude also increases away from the river; thus, flowing artesian wells are generally present only at the lower altitudes, within about 5 mi north and south of the San Juan River and along Montezuma Creek, where the potentiometric surface is above land surface. The high altitude of the Navajo aquifer in the Abajo Mountains, however, results in flowing wells only 15 mi south of the recharge area or about 30 mi north of the river (Avery, 1986, p. 28).

Hydraulic head in the Navajo aquifer is highest near the San Juan River. Water levels determined from pressure heads measured in wells N33 and N34 along the floodplain of the river near Aneth average about 245 ft above land surface. Vertical hydraulic gradients in the Navajo aquifer itself also can be present because of the thickness of the aquifer and the difference in horizontal and vertical hydraulic conductivity in the aquifer. Well N2 is reported to yield water from a depth of about 1,335 ft, with a water level during the study of about 110 ft above land surface, but the adjacent flowing well (N5) that was drilled to a depth of 600 ft and is open only to the Entrada Sandstone had a water level of about 33 ft above land surface. These intra-aquifer vertical head differences provide the potential to move water upward from the Wingate into the Navajo Sandstone and from the Navajo into the Entrada Sandstone.

Table 1. Records of selected wells and springs in the Navajo and other aquifers in and near the Greater Aneth Oil Field,

[deg, degrees; min, minutes; sec, seconds; —, no data; >, greater than; <, less than; ?, value uncertain]

Map number: Refer to figure 10.

Well/spring location: Refer to figure 2 for an explanation of the numbering system.

Primary use of water: S, stock; H, household; I, irrigation; P, public supply; U, unused; N, industrial; A, well plugged and abandoned.

Altitude of land surface: In feet above sea level.

Water level: In feet above (-) or below land surface; F, flowing, no measurement taken or possible.

Discharge: gal/min, gallons per minute; e, estimated, minimum value.

Map number	Well/spring location	Latitude (deg/min/sec)	Longitude	Property owner/ lease holder	Date of well completion	Primary use of water	Depth of well (feet)
Navajo aquifer							
N1	(D-38-25)35bda-1	372631	1090834	Bureau of Land Management	02-09-54	S	8,054
N2	(D-39-25) 5acb-2	372541	1091135	Hugh Benally	01-14-52	H,I	7,621
N3	(D-38-25)33bdc-1	372628	1091051	Bureau of Land Management	—	S	—
N4	(D-38-26)28acd-1	372722	1090355	Bureau of Land Management	01-17-53	S	5,681
N5	(D-39-25) 5acb-1	372542	1091135	Hugh Benally	07-00-51	H,I	600
N6	(D-39-26)21bdb-1	372303	1090420	National Park Service	09-25-63	P	1,440
N7	(D-40-23)20dbc-1	371735	1092438	Samson Resources	01-30-63	S	5,520
N8	(D-40-23)21dbc-1	371734	1092332	Elkhorn Operating	08-15-60	N	777
N9	(D-40-23)21dbc-2	371735	1092331	Elkhorn Operating	04-20-59	N	1,036
N10	(D-40-23)27baa-1	371710	1092238	Bureau of Land Management	12-11-58	N	672
N11	(D-40-24)14adb-1	371842	1091433	Texaco	03-31-57	A	1,070
N12	(D-40-24)15bcc-1	371838	1091628	Texaco	1956	A	900
N13	(D-40-24)17aac-1	371848	1091749	Navajo Nation	08-15-51	S	—
N14	(D-40-24)17dbd-1	371825	1091803	Texaco	05-01-56	A	925

Altitude of land surface (feet)	Water level (feet)	Date water level measured	Discharge (gal/min)	Date discharge measured	Remarks
Navajo aquifer					
4,850	-82	08-21-83	106	08-21-83	Former oil test; water flows from above 1,465 ft
			43.4	08-26-93	
4,760	-460	08-01-51	420	08-00-51	Former oil test; water flows from upper part of hole, above 1,335 ft
	-335	01-00-54	>100 e	08-26-93	
	-110	09-19-94			
4,790	-6	06-10-82	28	08-06-69	Water forms small pond
	-6.1	04-19-94	7.5	06-10-82	
			.9	08-26-93	
5,030	-47	09-21-82	15	06-09-82	Former oil test; yields water from 580-600 ft; well reported to have
	-49	08-21-83	31.5	08-26-93	originally yielded 140 gal/min
	-43	08-26-93			
4,760	-149	07-00-51	168	07-00-51	Water source for N2 well; water forms small pond
	-122	01-00-54	100	08-26-93	
	-47	02-19-83			
	-33	08-26-93			
5,240	113	09-25-63	29	09-25-63	Hovenweep National Monument well
	203.6	08-18-80	17	10-07-89	
	205	04-06-81			
	207.1	03-10-82			
	217.5	11-02-93			
4,520	-58	10-28-92	7.5	06-21-89	Flows from casing of former oil well, above 1,080 ft
			18	06-24-92	
4,540	-49	04-22-94	378	08-00-60	El Paso well No. 9; water piped to natural gas plant near Montezuma
			175	08-17-76	Creek
			267	08-04-81	
			50	04-22-94	Discharge is free-flowing
4,540	-54	04-22-94	250	04-26-59	El Paso well No. 8; plugged back to 908 ft from oil test;
			75	08-17-76	water piped to natural gas plant near Montezuma Creek
			209	08-04-81	
			57	04-22-94	Discharge is free-flowing
4,500	-74	05-18-83	19	06-14-82	El Paso well No. 7
	-42	10-28-92	87	02-19-83	
			48	04-22-94	
4,850	—	—	—	—	Well does not flow; appears to be blocked at 42-43 ft
4,560	-97	02-19-83	124	03-29-63	Plugged in 1994
	-51	10-26-92	85	02-19-83	
			7.5	05-15-89	
			9.3	06-26-92	
4,540	-6.2	10-26-92	1.3	08-25-92	Reported to be deep well
4,570	F	05-01-56	131	03-29-63	Plugged in 1993
	-5	10-26-92	9.0	03-11-82	
			25.7	06-22-92	

Table 1. Records of selected wells and springs in the Navajo and other aquifers in and near the Greater Aneth Oil Field,

Map number	Well/spring location	Latitude (deg/min/sec)	Longitude	Property owner/ lease holder	Date of well completion	Primary use of water	Depth of well (feet)
Navajo aquifer—Continued							
N15	(D-40-24)17dcd-1	371809	1091803	Navajo Nation	—	S	230 ?
N16	(D-40-24)19ada-1	371749	1091847	Navajo Nation	—	S	>500
N17	(D-40-25) 1bcc-1	372020	1090751	Navajo Nation	08-07-52	U	1,420
N18	(D-40-26)20adb-1	371748	1090451	Texaco	04-27-66	U	1,254
N19	(D-40-26)21abb-1	371802	1090356	Texaco	04-00-66	U	1,174
N20	N(B-34-20)10ccb-1	371311	1090238	Ute Mountain Reservation	09-26-59	S	5,938
N21	N(B-34-20) 3bad-1	371418	1090212	Smith Petroleum	08-02-57	N	5,839
N22	(D-41-23)16aaa-1	371353	1092316	Giant Exploration	07-09-64	U	932
N23	(D-41-23)12bda-1	371431	1092028	Mobil Oil	12-02-56	S	612
N24	(D-41-24)20dba-1	371227	1091758	Mobil Oil	05-27-58	U	604
N25	(D-41-24)27cac-1	371130	1091616	U.S. Oil and Gas	06-14-57	A	5,584
N26	(D-41-24)28cdb-1	371125	1091722	U.S. Oil and Gas	12-01-57	A	5,688
N27	(D-41-24)30bcc-1	371141	1091947	Navajo Nation	04-08-66	S	662
N28	(D-41-24)33dac-1	371038	1091648	U.S. Oil and Gas	01-23-58	A	5,660
N29	(D-41-24)33dbb-1	371047	1091705	U.S. Oil and Gas	10-12-57	A	5,655
N30	(D-41-25) 4cad-1	371457	1091050	Mobil Oil	02-18-58	S	1,098
N31	(D-41-25)12dac-1	371403	1090711	Navajo Nation	12-02-58	S	720
N32	(D-41-25)13aab-1	371341	1090706	Pan American Petroleum	12-13-64	U	5,854
N33	(D-41-25)17cbd-1	371311	1091206	Mobil Oil	08-27-64	U	717
N34	(D-41-25)17cdb-1	371303	1091156	Mobil Oil	08-10-64	U	5,480
N35	(D-41-25)21bba-1	371253	1091104	Navajo Nation	07-00-42	U	1,163
N36	NT(B-33-20)22bca-1	371048	1090101	Ute Mountain Reservation	06-19-59	U	5,938
N37	(D-42-22)14bbc-1	370828	1092832	Navajo Nation	10-00-51	U	590
N38	(D-42-23) 2bdb-1	371010	1092145	Clyde Toney	04-12-54	H,S	460

San Juan County, Utah—Continued

Altitude of land surface (feet)	Water level (feet)	Date water level measured	Discharge (gal/min)	Date discharge measured	Remarks
Navajo aquifer—Continued					
4,500	F	05-17-89	<1	05-17-89	Flows from open casing at ground level
4,580	F	06-23-92	9.0	06-23-92	Flows from open casing 4 ft above land surface
5,220	271	08-00-52	22	08-00-52	Abandoned windmill site; Tribal well 12T-312
	352.55	09-19-94	1.8	03-10-55	
4,980	F ?	04-18-66	60	09-21-94	Well V220; adjacent to Ismay injection facility
	60	07-22-82			
	59.5	09-19-94			
4,920	F	04-25-66	5.0	04-28-66	Well U121
	-42	11-04-93	36	11-04-93	
4,953	-9	05-05-93	.5	11-18-92	Former oil test; water flows from upper part of hole
4,874	F	08-31-92	—	—	Cache Unit water well #1; plugged back to 940 ft; water pumped to nearby injection facility
4,660	-14	07-09-64	5.4	03-10-83	Adjacent to abandoned injection facility
	-7.1	09-24-94	1.3	09-24-94	
4,620	F	12-02-56	31.5	12-02-56	Water forms small pond
	-9.3	10-26-92	5.4	01-18-83	
			6.4	06-25-92	
4,800	105	05-27-58	30	05-27-58	Well acquired by Mobil Oil from Phillips Petroleum in 1993
	140	06-15-93	25	06-18-93	
4,640	F	07-31-91	25 e	07-31-91	Flowed from producing oil well; water plugged off in 1991
4,720	-23	03-08-83	<5	10-11-89	Flowed from former oil test; plugged and abandoned 1991
4,820	111	04-08-66	2.0	01-19-83	Windmill; Tribal well 9T-559
4,720	-31	10-26-92	5 e	05-13-89	Flowed from injection well; plugged and abandoned 1992
4,690	-73.	03-08-83	20	08-28-92	Flowed from former oil test; plugged and abandoned 1992; water used for domestic and stock purposes
	-44	10-26-92			
4,720	F.	02-17-58	60	02-17-58	Water forms small pond
	-32	10-27-92	8.8	04-15-83	
			7.5	05-11-89	
			5.1	06-26-92	
4,776	-4.6	10-27-92	3.0	12-03-58	Abandoned windmill site; Tribal well 12T-504
			.1	05-07-82	
			<1	10-27-92	
4,800	F	04-15-83	18	04-15-83	Former oil test; plugged back to 1,860 ft; water flows from above
			<1	10-10-89	960 ft, from base of well marker
4,462	-180	06-15-64	60	06-15-64	Superior McElmo Creek Unit #26-N well
	-274	08-23-83	150 e	04-06-93	
	-247	04-21-94			
4,460	-130	03-09-64	72	03-09-64	Former oil test; Superior O-24 well; plugged back to 1,050 ft; yields
	-231	08-00-83	25	04-06-93	water from 500-600 ft
	-241	09-22-94			
4,520	F	08-23-89	75	09-09-54	Flows from hilltop above San Juan River; probably Tribal well
			100	08-23-83	12K-308
			60	04-20-94	
4,882	F	11-18-92	10 e	11-18-92	Former oil test; water flows from 1,094-1,098 ft from open casing below surface of large pond
5,130	315	12-03-53	15	10-00-51	Tribal well 9K-214; windmill not operational
	332.6	03-09-83			
4,760	F	10-21-54	35	04-12-54	
	-18.6	05-06-82	7.5	05-06-82	
	-13.5	08-25-93	4.0	06-15-93	

Table 1. Records of selected wells and springs in the Navajo and other aquifers in and near the Greater Aneth Oil Field,

Map number	Well/spring location	Latitude (deg/min/sec)	Longitude	Property owner/ lease holder	Date of well completion	Primary use of water	Depth of well (feet)
Navajo aquifer—Continued							
N39	(D-42-24) 5dac-1	370950	1091755	U.S. Oil and Gas	03-03-60	S	5,686
N40	(D-42-24)22dda-1	370705	1091539	Carter Oil	10-30-55	U	755
N41	(D-42-26)28bba-1	370642	1090435	Davis Oil	10-24-60	U	5,972
N42	N(B-33-20)15dcc-1	370557	1090028	Ute Mountain Reservation	08-15-56	U	6,252
N43	(D-43-23)15cab-1	370259	1092245	Navajo Nation	01-20-54	S	508
N44	(D-43-24)18aab-1	370320	1091900	Navajo Nation	02-18-35	S	735
N45	(D-43-24)12ada-1	370402	1091331	Navajo Nation	08-09-64	S	660
N46	(D-42-25) 8aba-1	370922	1091131	Southland Royalty	12-03-63	U	5,570
N47	(D-40-23) 4dbd-1	372010	1092330	Consolidated Oil and Gas	08-13-57	U	5,597
N48	(D-40-23) 3bcc-1	372020	1092302	Bureau of Land Management	—	S	—
N49	(D-40-23) 4ada-1	372030	1092307	Bureau of Land Management	—	S	—
N50	(D-40-24)17dca-1	371819	1091804	Texaco	—	U	—
N51	(D-40-24)35bad-1	371613	1091502	Texaco	1958	A	1,099
N52	(D-40-24)21aba-1	371803	1091659	Texaco	1958	A	1,347
N53	(D-40-22)23aca-1	371749	1092750	Hay Hot Oil	04-24-81	A	5,673
N54	(D-40-23)36abb-3	371622	1092019	Quinn Howe	07-10-82	N	380
N55	(D-40-24)26aaa -1	371709	1091431	Texaco	1958	U	1,085
N56	(D-41-26)20cda-1	371213	1090522	Navajo Nation	10-02-63	S	1,245
Alluvial aquifer							
A1	(D-41-26) 7dab-1	371411	1090604	Navajo Nation	04-16-65	S	<40
A2	(D-41-25)17cdb-1	371301	1091157	Mobil Oil	1963	H	28
A3	(D-41-25)27dca-1	371119	1090929	Navajo Nation	—	S	<40
Dakota aquifer							
D1	(D-39-26)33abc-S1	372124	1090404	Navajo Nation	11-13-41	S	—
Morrison aquifer							
M1	(D-41-26)33aca-1	371055	1090355	Navajo Nation	11-00-62	S	753
M2	(D-41-25)19bad-1	371243	1091259	U.S. Oil and Gas	—	U	<300 ?
M3	(D-42-23)15acc-S1	370813	1092233	Navajo Nation	—	U	—
Upper Paleozoic aquifer							
UPZ1	(D-41-24)18dab-1	371314	1091857	Mobil Oil	04-00-94	N	5,750
UPZ2	(D-38-23)13ddc-1	372838	1092000	Meridian Oil	06-04-87	N	6,068
UPZ3	(D-38-24) 3cac-1	373035	1091613	Duncan Oil	06-16-89	N	3,120
UPZ4	(D-39-25) 9adb-1	372447	1091018	Meridian Oil	07-11-87	N	5,612
UPZ5	(D-42-24)10aaa-1	370927	1091542	U.S. Oil and Gas	08-12-60	A	6,297

Altitude of land surface (feet)	Water level (feet)	Date water level measured	Discharge (gal/min)	Date discharge measured	Remarks
Navajo aquifer—Continued					
4,760	-32	10-26-92	<1	05-13-89	Former oil test; water flows from above 1,325 ft
4,880	F	11-17-92	.02	11-17-92	
4,760	F	08-23-89	10 e	08-23-89	Water flows from ground near sealed casing; initial well drilled to 1,880 ft and used as water well for deeper, adjacent well
4,975	-28	10-27-92	4	06-26-92	Former oil test; water flows from upper part of hole
5,200	133	01-20-54	20	01-20-54	Windmill; Tribal well 9K-219
	136.4	05-06-82	3.3	01-19-83	
5,320	309	02-18-51	10	02-18-35	Windmill; Tribal well 9Y-32
	354	05-05-81	<3	11-04-93	
5,220	430	08-09-64	1.8	05-05-82	Windmill; Tribal well 9T-539
4,683	F	04-01-93	37	04-01-93	Water flows from ground between two abandoned well markers; initial hole drilled to 3,173 ft
4,624	-33	07-16-93	1.0	07-16-93	Former oil test; water flows from above 964 ft
4,580	F	06-14-82	7.5	06-14-82	Water forms small lake
	-21	10-28-92	28.6	04-08-93	
4,580	F	06-14-82	2.1	06-14-82	
	-11	10-28-92	1.8	04-08-93	
4,560	F	06-16-89	15.7	08-24-93	Flows around outside of casing; planning to be plugged
4,640	F	06-25-92	5 e	06-25-92	Plugged in 1993
4,603	F	04-02-93	<1	04-02-93	Plugged in 1993
4,495	F	08-26-92	<1	08-26-92	Flowed from surface casing of former oil test; plugged in 1996
4,430	2 ?	07-10-82	1.7	03-07-83	Montezuma Creek laundromat well; yields water from Entrada Sandstone
	-36	03-07-83	7.2	09-23-94	
4,720	7.75	11-20-92	—	—	Casing open but well does not flow
	3.5	09-20-94	—	—	
5,160	275	05-07-82	<2	06-21-89	Windmill; Tribal well 12T-540
Alluvial aquifer					
4,918	—	—	—	—	Hand pump well; Tribal well Yellowmound #12-5-5
4,460	—	—	300	09-23-93	Water supply well No. 22; water used by Navajo residents
4,520	F	10-09-89	<1	10-09-89	Flows intermittently; remnant of hand-pump well
Dakota aquifer					
5,016	—	—	<1	06-16-93	Hand pump caps spring; possibly Tribal well 12R-163
Morrison aquifer					
4,850	247	05-07-82	<2	06-17-93	Windmill; Tribal well 12T-541
4,480	F	08-25-89	<1	08-25-89	Cathodic-protection well; adjacent to Section 19 satellite battery
4,760	—	—	<5	11-05-93	Desert Creek spring; discharges from Bluff Sandstone
Upper Paleozoic aquifer					
4,784	-333	04-17-94	—	—	18-43B injection well; water from 2,663 ft in Cutler Formation
5,109	—	—	—	—	Wash Unit #2 well; plugged back to 3,680 ft; water from Shinarump Member above 2,950 ft; water used for injection
5,227	—	—	—	—	Cave Canyon #1 well; water from Wingate, Shinarump, and Cutler Formations; water used for injection
4,857	—	—	—	—	42-9 well; plugged back to 3,115 ft; water from Wingate and Cutler Formations; water used for injection
5,448	—	—	—	—	Continental Oil Navajo C-18 well; water from 3,230-3,330 ft in DeChelly Sandstone

Computer simulations by Thomas (1989) indicate that both upward and downward movement of water between aquifers is likely, but that downward movement probably accounts for a substantial part of the recharge to deeper formations that do not crop out in areas where abundant precipitation is available for recharge. In parts of the study area, the potential for vertical ground-water movement as a result of differences in hydraulic head between the aquifers is downward from upper Paleozoic to middle Paleozoic rocks (Weiss, 1991, p. 28)(fig. 3). Natural movement of water from middle Paleozoic aquifers (Leadville Limestone) and upper Paleozoic aquifers and confining layers (Hermosa Group) to the middle Mesozoic aquifers (Navajo Sandstone) is therefore not likely in these parts of the area.

On the basis of differences in potentiometric contours, however, Freethey and Cordy (1991, fig. 58, p. C 83) showed that an upward gradient from the upper Paleozoic aquifer (Cutler Formation) to the middle Mesozoic aquifers (Navajo aquifer) was present in an area north and south of the San Juan River near Aneth (fig. 8). This interpretation was made by superimposing water-level contour maps of the middle Mesozoic and upper Paleozoic aquifers. Comparison of water-level altitudes for selected wells in the upper Paleozoic aquifer (determined from drill-stem test data) and in the middle Mesozoic aquifers (determined from measurement of water levels or pressure heads) in this area indicates that water levels in the upper Paleozoic aquifer were higher than water levels in the middle Mesozoic aquifers. This area of upward potential may be smaller or larger than that indicated by Freethey and Cordy (1991). Data from "Report of Water Encountered During Drilling" (Utah Division of Water Rights, unpub. data) also indicate that water levels (hydraulic head) in the upper Paleozoic aquifer are high enough to enable water to discharge at land surface in the vicinity of the Greater Aneth Oil Field. Barnes (unpub. data, 1959, p. 15) estimated that yields of as much as 100 gal/min were possible from the DeChelly Sandstone near the San Juan River.

Hydraulic-head values determined from drill-stem data from the upper Paleozoic aquifer were compared with water-level data from the Navajo aquifer to determine the potential for upward movement of water between these units. Density differences and osmotic-pressure gradients also affect movement of water through and between aquifers (Weiss, 1991, p. 25), but these effects were not evaluated and are probably relatively minor when compared with the driving forces

that result from differences in hydraulic head. Head differences determined from drill-stem test data and measured water levels substantiate that upward movement of water from the upper Paleozoic aquifer (Cutler Formation or DeChelly Sandstone Member) into the Navajo aquifer is possible in part of the study area (fig. 8). In an evaluation of the DeChelly Sandstone as a potential water source for Texaco water-flood operations (Barnes, unpub. data, 1959, p. 14), the shut-in pressure from a drill-stem test from a well in T. 40 S., R. 24 E., Sec. 25 showed that the hydraulic head in the DeChelly Sandstone was about 60 ft higher than the hydraulic head in the Navajo Sandstone, indicating that potential upward movement of water between these formations was possible in this area. Formation pressure from a wireline test of the DeChelly Sandstone in the Mobil 18-43B injection well (T. 41 S., R. 24 E., Sec. 18) was used to calculate shut-in pressure of the formation at a depth of 2,663 ft (James Vanderhill, Mobil Exploration and Producing, U.S., Inc., written commun., 1995). By using the Weigel (1987, p. 9) formula

$$H = A - D + 2.33 \times P_f \quad (1)$$

where:

H is shut-in head, in ft above sea level,
 A is altitude of land surface at the well,
 D is depth of drill-stem test interval,
 P_f is formation pressure, in pounds per square inch, and

2.33 is a constant to convert formation pressure to equivalent freshwater head, in ft, a head of 5,117 ft was obtained, compared with a head (water-level altitude) of about 4,660 ft in the Navajo aquifer in this area (fig. 8). Similar calculations using pump-test data from Mobil's Ratherford Unit 14-33 well in T. 41 S., R. 23 E., Sec. 14 also indicate that hydraulic head in the DeChelly Sandstone at a depth of about 2,500 ft exceeded that in the Navajo aquifer by about 300 ft, thus confirming a potential for upward vertical movement in this area.

Drill-stem test data from selected wells in the DeChelly Sandstone in the Boundary Butte Oil Field in the southwestern part of the study area (fig. 1) indicate that hydraulic head in the Navajo aquifer exceeds that in the DeChelly Sandstone by less than 100 ft (Whitfield and others, 1983, table 14, p. 75) and indicate that the potential for vertical movement of water is downward from the Navajo aquifer to the upper Paleozoic aquifer in this area. These wells are located outside and southwest of the area of upward potential (fig. 8) as outlined by Freethey and Cordy (1991). Relative differ-

ences between hydraulic head in the upper Paleozoic and Navajo aquifers for these and several other wells shown in figure 8 are consistent with the head relations determined by Freethy and Cordy (1991); however, hydraulic-head data for some wells in the upper Paleozoic aquifer were determined from historical drill-stem test data and compared with water-level altitudes in the Navajo aquifer that were determined during this study. A contemporary comparison of hydraulic-head data from both the upper Paleozoic and Navajo aquifers for these wells would help verify and refine the head relations between these aquifers.

Water-level declines in the Navajo aquifer increase the potential for upward movement of water from underlying aquifers, such as the upper Paleozoic aquifer, because the hydraulic gradient between the Navajo and the upper Paleozoic aquifer is substantially increased. In areas where the calculated differences between hydraulic head in the upper Paleozoic and Navajo aquifers are less than 100 ft, as in the Boundary Butte Oil Field area, water-level declines could potentially reverse the hydraulic gradient and create a potential for upward movement of water. Implications for upward movement of water from the upper Paleozoic aquifer to the Navajo aquifer are discussed in subsequent sections of this report.

Potential Avenues of Ground-Water Movement

Because water in the upper Paleozoic aquifer is geochemically similar to water from many wells in the Navajo aquifer (discussed in subsequent sections of this report), and hydraulic head in the upper Paleozoic aquifer is higher than hydraulic head in the Navajo aquifer in a part of the study area (fig. 8), saline water from the upper Paleozoic aquifer potentially could have moved upward into the Navajo aquifer and caused salinization. Possible avenues for upward movement of saline water from the upper Paleozoic aquifer to the Navajo aquifer include (1) migration upward through fractures and matrix porosity in the overlying confining units of the Chinle and Moenkopi Formations; (2) migration upward through the long string casing of plugged and abandoned wells; (3) migration upward through annuli between the well casing and borehole walls of producing oil wells and injection wells, and plugged and abandoned wells; or (4) a combination of these avenues.

Fractures enhance vertical movement of water between aquifers, particularly in confining units where hydraulic-conductivity values are small; but fractures likely are not vertically continuous in thick sedimentary

sections or open at depth because of overburden pressure and secondary cementation. The Chinle and Moenkopi Formations between the Cutler Formation (upper Paleozoic aquifer) and Navajo aquifer (fig. 3) are about 1,200 ft thick in the vicinity of the Greater Aneth Oil Field and are estimated to have an average vertical hydraulic-conductivity value of only about 0.0011 ft/d (Jobin, 1962, pl. 1). Assuming an effective matrix porosity of about 15 percent for shales and intermixed siltstones and sandstones (Freeze and Cherry, 1979, p. 37) and a hydraulic-head difference of about 450 ft, on the basis of formation pressure data from the Mobil 18-43B well and from potentiometric-contour data in this area (fig. 8), an average linear velocity of about 0.0027 ft/d is obtained (Freethy and others, 1994, p. 7). Thus, about 1,200 years would be required for water to move from the Cutler Formation up to the base of the Navajo aquifer (Wingate Sandstone) and mix with water in this formation. If open fractures are locally present to enhance upward movement of water, travel time could be substantially less. Because the hydraulic-head value used in this example is probably larger than average when compared with other head data for wells in this area, average linear velocity would be less and travel time would be considerably greater. Nonetheless, anomalously high levels of salinity documented in water from some wells (N17 and N35) prior to discovery and development of the Greater Aneth Oil Field indicate natural pathways for the movement of saline water into the Navajo aquifer or an in situ source of salinity (discussed in subsequent section of report).

Borehole casings of plugged and abandoned oil wells and dry holes are a potential avenue through which water could move from the upper Paleozoic aquifer to the Navajo aquifer in some areas. Casing corrosion from saline water in the Cutler Formation has been documented in modern oil-field operations, but upward movement of water from these strata through the wellbore is generally inhibited by the weighted mud used in completion of the well (Larry Schlotterback, Texaco Exploration and Production, Inc., written commun., 1994). The Navajo aquifer may have been more susceptible to salinization in older oil wells and exploratory drill holes that were not plugged and abandoned according to current standards and procedures, particularly those plugged and abandoned prior to discovery of the Aneth Field; those in which the integrity of the cement and mud used to plug the wells has been compromised throughout time; and those in which surface casing was set to a depth insufficient to provide protection of all freshwater zones. In these wells, saline water

that may breach the long string casing could potentially move uphole and corrode through other parts of the casing where salinization of the Navajo aquifer might take place.

Annuli between the long string casing and the borehole walls (outside the casing) of active producing and injection wells, and plugged and abandoned wells, are an additional avenue for potential movement of saline water between the upper Paleozoic aquifer and the Navajo aquifer in some areas, particularly in older oil wells and dry holes that were not plugged and abandoned according to current standards and procedures. Investigation by the Navajo Nation Environmental Protection Agency during this study indicates that almost 200 active producing oil wells and injection wells were completed in a manner that did not completely isolate the upper Paleozoic aquifer from the Navajo aquifer and therefore, could allow crossflow between these units (Melvin Capitan and James Walker, Navajo Nation Environmental Protection Agency, written commun., 1994). In these wells, the depth of surface casing is above the base of the Navajo aquifer, which averages about 1,500 ft, and the top of the cemented interval is typically at a depth of 3,500 ft or greater. Because the depth of the top of the Cutler Formation generally is above 3,500 ft, an avenue or conduit could exist for water to move from the Cutler Formation to the Navajo aquifer where relative head differences are conducive to upward flow. Upward movement of water between these units, however, could be inhibited by collapse of the borehole walls in less-competent intervals in the confining units (Gilbert Hunt, Utah Division of Oil, Gas, and Mining, oral commun., 1995) and by the weighted mud that would be present in the uncemented interval. Nonetheless, water that discharges from the ground around plugged and abandoned wells N32, N41, and N46 indicates that upward movement of water outside of well casings or from boreholes that have been plugged is taking place.

SAMPLING, ANALYTICAL METHODS, AND QUALITY ASSURANCE

Water samples collected during this study were analyzed for major and minor cations and anions, selected trace elements, total organic carbon, dissolved-solids concentration, density, and the isotopic ratios of oxygen-18/oxygen-16, hydrogen-2 (deuterium)/hydrogen-1, sulfur-34/sulfur-32, and strontium-87/strontium-86. All water samples except those collected for isotopic analysis were analyzed at the U.S.

Geological Survey National Water Quality Laboratory in Arvada, Colorado. Analytical methodology used at the National Water Quality Laboratory is described in Techniques of Water-Resources Investigations of the U.S. Geological Survey (Fishman and Friedman, 1989). The stable isotope values for oxygen, hydrogen, and sulfur (sulfate) in water samples were determined at the U.S. Geological Survey Stable Isotope Laboratory in Reston, Virginia. Isotope values for strontium in water samples were determined at the U.S. Geological Survey Strontium Isotope Laboratory in Lakewood, Colorado.

Isotopic values for oxygen, hydrogen, sulfur, and strontium are expressed in the δ notation as permil differences between the sample and a standard. With oxygen, for example, $\delta^{18}\text{O}$ is defined by

$$\delta^{18}\text{O} = \frac{\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{\text{sample}} - \left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{\text{standard}}}{\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{\text{standard}}} \times 1,000 \quad (2)$$

where:

$(^{18}\text{O}/^{16}\text{O})_{\text{sample}}$ is the isotope ratio of the sample, and

$(^{18}\text{O}/^{16}\text{O})_{\text{standard}}$ is the isotope ratio of seawater.

The comparative standard for oxygen, hydrogen, and strontium isotopes is standard mean ocean water (SMOW). The comparative standard for sulfur is an iron sulfide in the Canyon Diablo meteorite and is referred to as the Canyon Diablo troilite (Drever, 1988, p. 368). δ notation in permil for the other isotopes is δD (hydrogen-2/hydrogen-1), $\delta^{34}\text{S}$ (sulfur-34/sulfur-32), and $\delta^{87}\text{Sr}$ (strontium-87/strontium-86). Specific analytical methods used in the analysis of each chemical constituent, reporting units, and minimum reporting levels are summarized in table 2.

Water samples collected for analysis of major and minor ions, trace elements, dissolved-solids concentration, and $\delta^{34}\text{S}$ were filtered on site through a 0.45-micron filter using a peristaltic pump and collected in field-rinsed polyethylene bottles. Water samples collected for $\delta^{18}\text{O}$, δD , $\delta^{87}\text{Sr}$, and total organic carbon analysis were unfiltered and collected directly from the wellhead. Water sampled from flowing wells was collected and processed immediately. Water sampled from wells powered by windmills was collected from the discharge line after the windmills had been operating for at least 1 day. Water from wells that had to be pumped and those that had valves to control artesian flow were sampled after 2 to 3 hours or until about three casing volumes were removed to obtain samples that were representative of the aquifer. Temperature,

Table 2. Analytical methods, reporting units, and minimum reporting levels for chemical constituents and physical properties analyzed in water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, 1989-94

[Method codes and analytical methods from Fishman and Friedman (1989) for inorganic constituents and Wershaw and others (1987) for total organic carbon; TWRI, Techniques of Water-Resources Investigations; N.A., not applicable; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; mg/L , milligrams per liter; g/ml , grams per milliliter; $\mu\text{g}/\text{L}$, micrograms per liter; permil, per thousand]

Chemical constituent/ physical property	TWRI method code	Reporting unit	Minimum reporting level
pH (lab)	I258785	units	N.A.
Specific conductance (lab)	I278185	$\mu\text{S}/\text{cm}$	1.0
Total alkalinity as CaCO_3 (lab)	I203085	mg/L	1.0
Density (lab)	I131285	g/ml	.990
Calcium	I115285	mg/L	.1
Chloride	I205785	mg/L	.1
Magnesium	I144785	mg/L	.1
Potassium	I163085	mg/L	.1
Sodium	I173585	mg/L	.1
Sulfate	I205785	mg/L	.1
Barium	I108485	$\mu\text{g}/\text{L}$	100
Boron	I111486	$\mu\text{g}/\text{L}$	10
Bromide	I212985	mg/L	.01
Fluoride	I232778	mg/L	.1
Iodide	I237185	mg/L	.001
Iron	I138185	$\mu\text{g}/\text{L}$	10
Lithium	I142585	$\mu\text{g}/\text{L}$	10
Manganese	I145485	$\mu\text{g}/\text{L}$	10
Silica	I270085	mg/L	.1
Strontium	I180085	$\mu\text{g}/\text{L}$	10
Strontium (isotope dilution)	(1)	$\mu\text{g}/\text{L}$	10
Vanadium	I288085	$\mu\text{g}/\text{L}$	1.0
Del deuterium	(2)	permil	N.A.
Del oxygen-18	(3)	permil	N.A.
Del strontium-87	(1)	permil	N.A.
Del sulfur-34	(4)	permil	N.A.
Total organic carbon	O310083	mg/L	.1
Solids, residue on evaporation at 180°C	I175085	mg/L	1.0

¹Analytical method described in Peterman (1990).

²Analytical method described in Kendall and Coplen (1985).

³Analytical method described in Epstein and Mayeda (1953).

⁴Extraction and analytical method described in Coleman and Moore (1978); Tabatabai (1992); and R.W. Carmody (U.S. Geological Survey, Reston, Virginia, written commun., 1995).

pH, and specific conductance also were monitored until values had stabilized before samples were taken. Surface-water samples collected from the San Juan River were composited in equal-width increments based on techniques described by Ward and Harr (1990). Samples of produced (formation) and comingled water were collected from water storage tanks at injection facilities and represent composite samples of mixed water from numerous wells. Precipitation (snow) samples from the Abajo Mountains were collected directly from snowbanks near established streamflow-gaging stations.

Water samples analyzed for $\delta^{18}\text{O}$, δD , and total organic carbon concentration were collected in brown, baked glass bottles. Water samples collected before 1993 for $\delta^{18}\text{O}$, δD , and $\delta^{34}\text{S}$ analysis were preserved with mercuric chloride to inhibit growth of microorganisms and those collected after 1993 were not preserved. Water samples for $\delta^{87}\text{Sr}$ analysis were collected in acid-rinsed polyethylene bottles and were not preserved. Water samples collected for major and minor ions and trace-element analysis were preserved with nitric acid to a pH of less than 2 to prevent precipitation of dissolved constituents between field collection and laboratory analysis. Water samples collected for total organic carbon analysis were chilled to 4°C to inhibit degradation of organic material.

Temperature, pH, specific conductance, and alkalinity were determined in the field at the time of water sample collection using U.S. Geological Survey procedures outlined in Wood (1976). Values for alkalinity, bicarbonate, and carbonate were determined by titration techniques (Wood, 1976). Specific conductance, pH, and alkalinity also were determined in the laboratory from unfiltered water samples submitted for chemical analysis. Specific conductance and pH were calibrated with standards in the range of the water-sample values and generally were within 5°C of well-water temperature before actual sample values were determined. Temperature was measured at the discharge point to the nearest 0.5°C.

Water levels in flowing wells were determined by using pressure gages that measure feet above land surface either directly or in pounds of pressure, which can be converted to feet. Water levels in non-flowing wells were measured using either electrically sensitive probes or steel tapes. Water levels were measured to the nearest 0.1 ft, when possible. Discharge from flowing wells was determined volumetrically or using a calibrated Parshall flume, in gallons per minute (Rantz and others, 1982, v. 2, p. 314).

The chemical data used in this study were compiled from both U.S. Geological Survey and non-U.S. Geological Survey sources and cover more than 40 years (Mayhew and Heylmun, 1965; Avery, 1986; Rosenbauer and others, 1992; Kimball, 1992; and Spangler, 1992). Because the chemical data were not generated under uniform sampling and analytical protocols, quality-assurance and quality-control information are not available to assess the adequacy of the water-sample collection techniques or analytical methodology. Therefore, the data collected and analyzed from single wells must be interpreted with caution, particularly when comparing data collected and compiled during this study with older data. In addition, because of the general scarcity of data for most wells, overall trends in data with time from single wells also must be interpreted with caution. Nonetheless, the collective data are probably representative of ground-water chemistry in this area during the past 40 years.

A series of quality assurance (QA) water samples were collected, processed, and submitted along with routine water-quality samples collected during 1992–94. All QA samples were submitted “blindly” to the National Water Quality Laboratory in Arvada, Colorado.

Two standard reference water samples (SRWS) were used to monitor laboratory performance for major-, minor-, and trace-element concentrations during the project. The SRWS T101 from the U.S. Geological Survey in Ocala, Florida, was selected to monitor the performance of trace- and minor-element analyses, and a standard seawater sample from Kahl Scientific was used to monitor the performance of major-element analyses. A seawater standard was selected because of its stability and because this standard best matches the matrix of the more saline water in the study area.

The most probable values determined from SRWS T101 and the standard seawater are compared with the analytical results obtained from the National Water Quality Laboratory in table 3. The analytical results for SRWS T101 were accurate, with the mean value agreeing within one standard deviation of the most probable value. The analytical precision for the elements determined in this standard also was within acceptable limits.

The most probable concentrations from the seawater standard were calculated from the chlorinity of the seawater standard used during the study (table 3) according to the method outlined by Stumm and Morgan (1981, p. 567). Except for calcium, the seawater samples analyzed during the study had consistently

Table 3. Most probable standard reference water values for selected major- and trace-element constituents compared with the values for standard reference water samples submitted with samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, November 1992 to September 1994

[µg/L, micrograms per liter; T101, U.S. Geological Survey standard reference water sample; mg/L, milligrams per liter; STDSW, standard seawater (chlorinity = 19.371 parts per thousand); ND, not determined]

Most probable value: Calculated according to method outlined in Stumm and Morgan (1981, p. 567).

Chemical constituent	Unit	Sample	Most probable value			Study value		
			Number of samples	Mean	Standard deviation	Number of samples	Mean	Standard deviation
Boron	µg/L	T101	22	370	50	6	365	16.4317
Lithium	µg/L	T101	14	68	5.7	6	70.00	.00
Silica	mg/L	T101	27	6.97	.470	6	7.23	.1751
Strontium	µg/L	T101	23	1,200	88	6	1,180	75.2773
Vanadium	µg/L	T101	16	16.9	4.7	5	17.20	1.3038
Calcium	mg/L	STDSW	ND	420	ND	5	420	23
Chloride	mg/L	STDSW	ND	19,800	ND	5	19,200	837
Magnesium	mg/L	STDSW	ND	1,330	ND	5	1,260	55
Potassium	mg/L	STDSW	ND	410	ND	5	382	13
Sodium	mg/L	STDSW	ND	11,000	ND	5	10,360	590
Sulfate	mg/L	STDSW	ND	2,780	ND	5	2,740	152

lower major-ion concentrations relative to the most probable value; however, the concentrations were always within plus or minus 10 percent of the most probable value (table 3). The relative standard deviation of the major-ion determinations did not exceed 6 percent.

Deionized, distilled water of known major-, minor-, and trace-element composition from the U.S. Geological Survey Water-Quality Service Unit, Ocala, Florida, was used for both trip and process blanks during each sampling trip. Six trip- and six process-blank samples were submitted for analysis after field trips from November 1992 to September 1994 (tables 4 and 5). The trip blank was used to monitor sample contamination from the sample container as well as contamination introduced during storage and transport of the samples. The trip blanks were prepared immediately before each trip, transported to the field, and stored, shipped, and analyzed with routine field samples collected during each trip. Median concentrations of minor and trace elements analyzed in the trip blanks were all less than the analytical detection limits; however, the highest reported concentrations of iron, vanadium, and iodide slightly exceeded the lower detection limits (table 4).

The process blanks were used to assess contamination during field processing of water samples. After a routine water sample from a well was processed, the

collection and filtering apparatus was cleaned according to standard procedures (Sylvester and others, 1990). The deionized, distilled water process blank was then processed through the same equipment and analyzed for major-, minor-, and trace-element concentrations. Median concentrations for the process blanks were at or slightly above the analytical detection limits (table 5). Calcium, chloride, sulfate, and strontium were the only constituents with a median value slightly above the limit of detection.

Field duplicates were collected to ensure consistency in the methods used to collect the water samples. One duplicate sample from a randomly selected well was collected, processed, and submitted for minor-, trace-element, and specific-conductance analyses during each sampling trip from November 1992 to September 1994 (table 6). Although most field duplicate results agree within plus or minus 10 percent of the concentration or value of the regular sample, discrepancies were noted in selected samples collected during the November 1992, April 1994, and September 1994 trips. In these samples, concentrations of fluoride, iron, strontium, vanadium, and (or) bromide were more than plus or minus 10 percent different than the comparable values of the respective samples. The chemical constituents with the most discrepancies were fluoride (2) and iron (2) (table 6). The source of these discrepancies is likely the result of varying analytical procedures

Table 4. Chemical analysis of selected minor- and trace-element constituents and physical properties from blank samples transported to and from the Greater Aneth Oil Field, San Juan County, Utah, November 1992 to April 1994

[µg/L, micrograms per liter; <, less than reported value; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

Chemical constituent/ physical property	Unit	Number of samples	Concentration		
			Median	Low	High
Barium	µg/L	6	<2	<2	<2
Boron	µg/L	6	<10	<10	<10
Bromide	mg/L	6	<.01	<.01	<.01
Fluoride	mg/L	6	<.1	<.1	<.1
Iodide	mg/L	6	<.001	<.001	.002
Iron	µg/L	6	<3	<3	3
Lithium	µg/L	5	<4	<4	<4
Manganese	µg/L	5	<1	<1	<1
Silica	mg/L	6	<.1	<.1	<.1
Strontium	µg/L	5	<.5	<.5	<.5
Vanadium	µg/L	6	<1.0	<1.0	1.2
Specific conductance	µS/cm	6	2	1	4

(Alfred Driscoll, U.S. Geological Survey National Water Quality Laboratory, oral commun., 1995). Agreement between the field duplicates and the regular samples for other chemical constituents was excellent.

CHEMICAL QUALITY OF GROUND WATER

Dissolved-solids concentrations in water from the Navajo aquifer are highly variable in the vicinity of the Greater Aneth Oil Field and are an anomaly when compared with water from the Navajo aquifer elsewhere in the State of Utah (fig. 11). Ground-water samples from the Navajo aquifer in the study area show a median specific-conductance value of about 3,000 µS/cm (slightly saline); median specific conductance of ground-water samples outside the area of the Greater Aneth Oil Field (in the State of Utah) is only about 550 µS/cm (freshwater). Chemical quality of water in the Navajo aquifer for selected wells is presented in tables 7 and 8. Results of chemical analysis for wells and springs in the alluvial, Dakota, Morrison, and upper Paleozoic aquifers, as well as samples of oil-field brine (OFB), non-oil-field brine (non-OFB), surface water, and precipitation also are presented in tables 7 and 8.

Dissolved-solids concentrations in water from 56 wells in the Navajo aquifer in the study area ranged from 145 mg/L to as much as 17,300 mg/L (pl. 1). Dissolved-solids concentrations in water from 17 wells was less than 1,000 mg/L, indicating freshwater (Heath, 1989, table 2, p. 65). Dissolved-solids concen-

trations in water from 20 wells was between 1,000 and 3,000 mg/L (slightly saline). Water from 14 wells had dissolved-solids concentrations between 3,000 and 10,000 mg/L (moderately saline), and water from 5 wells had dissolved-solids concentrations between 10,000 and 20,000 mg/L (very saline).

Dissolved-solids concentrations in water from selected wells and springs in the alluvial, Dakota, and Morrison aquifers ranged from 543 to as much as 3,800 mg/L (pl. 1). Generally, dissolved-solids concentrations in water from these aquifers is less than 1,000 mg/L, on the basis of specific-conductance measurements taken during the study. The highest dissolved-solids concentration in water from alluvial aquifers was 3,800 mg/L in well A1. Dissolved-solids concentration in spring D1, which discharges from the Dakota Sandstone, was 2,650 mg/L. The highest concentration of dissolved solids in water from the Morrison aquifer was 3,200 mg/L in well M2.

Dissolved-solids concentrations in water from selected wells completed in the upper Paleozoic (Cutler Formation) aquifer and lower Mesozoic Shinarump Member of the Chinle Formation ranged from 2,520 to 27,600 mg/L (pl. 1), indicating a substantial variance in salinity. A dissolved-solids concentration of 52,187 parts per million and a chloride concentration of 31,700 parts per million were reported in water from a drill-stem test of the DeChelly Sandstone in a well in T. 41

Table 5. Chemical analysis of selected major-, minor-, and trace-element constituents from blank samples processed on site in and near the Greater Aneth Oil Field, San Juan County, Utah, November 1992 to September 1994

[mg/L, milligrams per liter; <, less than reported value; µg/L, micrograms per liter]

Chemical constituent	Unit	Number of samples	Concentration		
			Median	Low	High
Calcium	mg/L	6	0.05	<0.02	0.08
Chloride	mg/L	6	.2	.1	.3
Magnesium	mg/L	6	<.01	<.01	.01
Potassium	mg/L	6	<.1	<.1	<.1
Sodium	mg/L	6	<.2	<.2	.3
Sulfate	mg/L	6	.35	<.1	.8
Barium	µg/L	6	<2	<2	<2
Boron	µg/L	6	<10	<10	<10
Bromide	mg/L	6	<.01	<.01	<.01
Fluoride	mg/L	6	<.1	<.1	.1
Iodide	mg/L	6	<.001	<.001	.001
Iron	µg/L	6	<3.0	<3.0	12
Lithium	µg/L	6	<4	<4	<4
Manganese	µg/L	5	<1	<1	<1
Silica	mg/L	6	<.1	<.1	<.1
Strontium	µg/L	6	2	1	4
Vanadium	µg/L	6	<1	<1	<1
Dissolved solids	mg/L	6	<1	<1	2

S., R. 25 E., Sec. 17 (J.G. Crawford, unpub. data, n.d., Rocky Mountain oil-field waters, p. 64, table 35).

Howells (1990) mapped the depth to the base of moderately saline ground water (3,000 to 10,000 mg/L) in San Juan County, Utah. The base of moderately saline ground water was defined as the top of the first permeable interval containing water with a dissolved-solids concentration greater than 10,000 mg/L. The configuration of the base of moderately saline ground water is affected by stratigraphy and geologic structure; thus, Howells' map indicates that the altitude of the base of moderately saline water ranges from as low as 1,500 ft in the southwestern part of the study area to as high as 4,500 ft in the northeastern part of the area. Consequently, water with dissolved-solids concentrations greater than 10,000 mg/L may be less than 500 ft below land surface in places in the Greater Aneth Oil Field. Howells' map also indicates valleys or troughs in the base of moderately saline water, implying inflow of fresh or less saline water from adjacent mountain recharge areas.

Stiff diagrams can be used to illustrate the relative concentrations of cations and anions in water from wells, to understand changes in water chemistry along ground-water flow paths, and to distinguish different water types (Stiff, 1951). Stiff diagrams for selected wells and springs in the study area are shown on plate 1. Results of chemical analysis of water from wells in the Navajo aquifer indicate that the major cation is sodium, regardless of the salinity concentration. Sodium is also the major cation in water from wells and springs in overlying aquifers in the study area (pl. 1). The high concentrations of sodium relative to calcium are attributed to water-rock interactions along ground-water flow paths from recharge to discharge areas, because in upgradient areas, sodium also is predominant in freshwater that contains low concentrations of chloride. Increased levels of sodium may be the result of precipitation of calcium carbonate, hydrolysis of sodium feldspars, or ion-exchange reactions (Kimball, 1992, p. 98). Excess concentrations of sodium also might result from mixing with sodium chloride type water in downgradient areas.

Table 6. Chemical analysis of selected minor- and trace-element constituents and physical properties from duplicate samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, November 1992 to September 1994

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; <, less than reported value; ND, not determined]

Map number: Refer to table 1 and figure 10; DUP, designates field duplicate sample for corresponding map number.

Map number	Fluoride (mg/L)	Silica (mg/L)	Barium (µg/L)	Boron (µg/L)	Iron (µg/L)	Manganese (µg/L)	Strontium (µg/L)	Vanadium (µg/L)	Lithium (µg/L)	Iodide (mg/L)	Bromide (mg/L)	Specific conductance (µS/cm)
Collected on November 16, 1992												
N41	0.6	10	<100	240	<10	ND	1,100	2.4	710	0.019	0.25	3,250
DUP	2.3	10	<100	250	<10	ND	1,100	<1.0	700	.012	.09	3,210
Collected on April 1, 1993												
N46	2.9	8.7	<100	2,500	30	30	4,800	34	1,200	.027	.69	8,390
DUP	2.9	8.7	<100	2,500	30	30	4,800	34	1,200	.027	.69	8,390
Collected on June 16, 1993												
D1	1.1	14	<100	120	<10	<10	3,200	3.2	370	.009	.52	3,600
DUP	1.1	13	<100	130	<10	<10	3,300	3.5	370	.009	.52	3,630
Collected on November 4, 1993												
N44	1.0	13	<100	110	13	1	38	270	10	.006	.04	660
DUP	.9	13	<100	110	12	1	33	280	9	.006	.04	660
Collected on April 21, 1994												
UPZ3	1.5	11	<100	700	510	60	5,100	8.4	530	.140	2.2	4,610
DUP	2.7	11	<100	700	250	60	5,200	8.9	530	.130	2.2	4,560
Collected on September 21, 1994												
N17	.7	11	<100	5,400	6,800	310	5,900	ND	2,000	.290	2.4	15,000
DUP	.7	10	<100	5,600	8,000	310	5,200	ND	2,000	.300	2.5	14,700

The major anions in water from wells in the Navajo aquifer are bicarbonate, sulfate, and chloride. In most recharge waters, bicarbonate is the major anion, probably from dissolution of calcite cement and because bicarbonate is the major anion in precipitation. Concentrations of sulfate in water could be derived from oxidation of sulfide minerals, particularly pyrite (Kimball, 1992, p. 98), possible dissolution of gypsum, or from mixing with saline water in downgradient areas. High concentrations of chloride are not present in water from the Navajo aquifer in upgradient areas; consequently, high concentrations of chloride in water in downgradient areas are the result of mixing with saline water or possibly from localized dissolution of

evaporite minerals in the Navajo aquifer (refer to next section of report). Because of the wide range of dissolved-solids concentrations in the upper Paleozoic aquifer (pl. 1), dissolved-solids concentrations in water from the Navajo aquifer, particularly sulfate and chloride concentrations, also could be expected to vary substantially throughout the study area, if mixing between these units takes place. This observed variance in salinity also might be explained by localized areas of more mineralized water in the Navajo aquifer (Buck Steingraber, Mobil Exploration and Producing, U.S., Inc., oral commun., 1993).

The major anions and cations form the basis for three main water types that can be related to salinity.

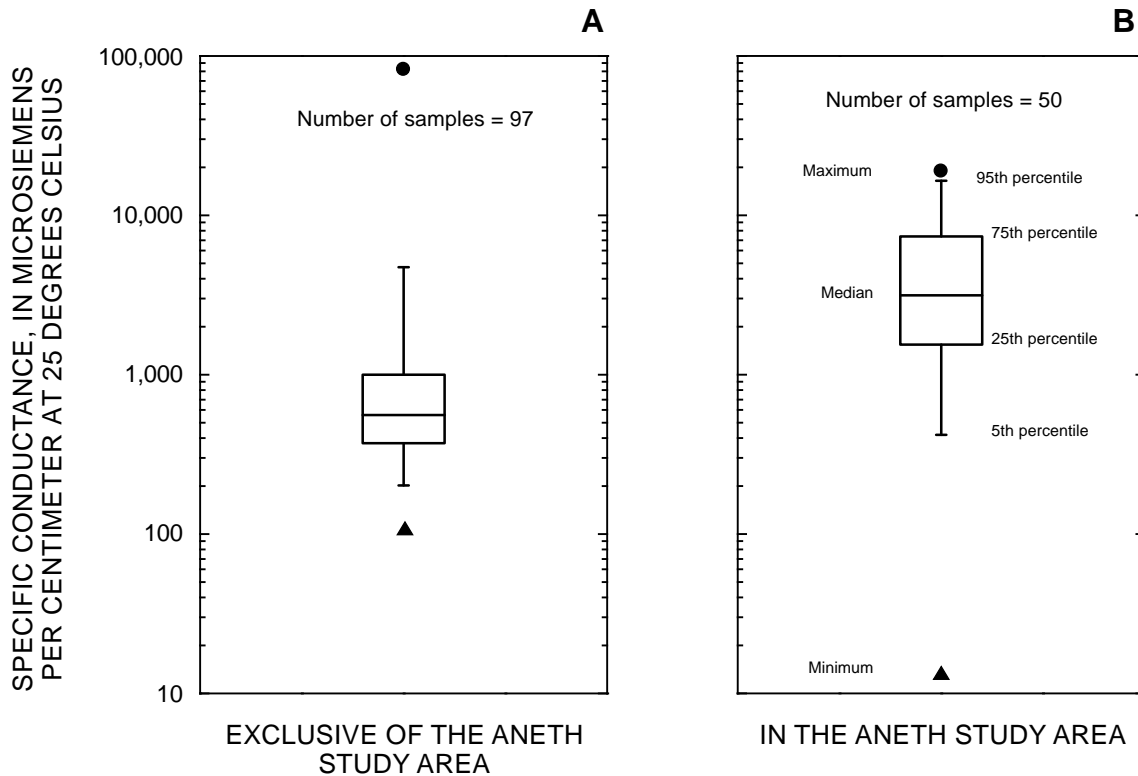


Figure 11. Relation of the specific conductance of water from the Navajo aquifer from wells and springs in the State of Utah.

Generally, water from wells classified as sodium bicarbonate or the subtypes, sodium bicarbonate chloride and sodium bicarbonate sulfate, had dissolved-solids concentrations less than 3,000 mg/L (pl. 1). Two subtypes of sodium sulfate water also were distinguished on the basis of salinity. Water with a dissolved-solids concentration between 1,000 and 3,000 mg/L was characterized as sodium sulfate bicarbonate type, and all but two samples with sodium sulfate chloride type water had dissolved-solids concentrations greater than 5,000 mg/L. All but one water sample characterized as sodium chloride sulfate type had dissolved-solids concentrations exceeding 7,000 mg/L. Water that was characterized as sodium chloride bicarbonate type had

dissolved-solids concentrations between 2,000 and 5,000 mg/L.

On the basis of the relation between water type and salinity, freshwater with a dissolved-solids concentration less than 1,000 mg/L is generally bicarbonate-dominated with relatively minor concentrations of sulfate and chloride. As salinity increases to about 3,000 mg/L (slightly saline), sulfate and chloride concentrations increase relative to bicarbonate and some water becomes sulfate- and chloride-dominated. Finally, as salinity increases beyond 5,000 mg/L (moderately saline), water is sulfate- or chloride-dominated, and bicarbonate is present in relatively lesser concentrations. Results of analysis indicate that water from the upper Paleozoic aquifer is a sodium chloride, sodium

Table 7. Selected physical properties and major- and minor-chemical constituents in surface- and ground-water samples and

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; g/ml, grams per milliliter; mg/L, milligrams per liter; —, no data;

Map number: Refer to table 1 and figure 10.

Sodium: K, reported value includes potassium.

Map number	Date sampled	Water temperature (°C)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	pH, field (standard units)	pH, lab (standard units)	Density (g/ml at 20 °C)	Hardness, total (mg/L as CaCO ₃)	Alkalinity, field (mg/L as CaCO ₃)	Alkalinity, lab (mg/L as CaCO ₃)	Solids, sum of constituents, dissolved (mg/L)	Solids, residue at 180°C, dissolved (mg/L)
Navajo aquifer												
N1	08-26-93	18	1,140	—	8.2	—	0.998	—	—	—	—	—
	06-20-84	18.6	1,140	1,180	8	8	—	29	494	484	704	700
	06-10-82	15.5	1,550	1,570	8.4	8.7	—	41	—	617	926	—
N2	08-26-93	19	1,490	—	8	—	.998	—	—	—	—	—
	06-19-84	19.3	1,980	1,720	8	7.9	—	44	504	507	1,010	998
	08-12-53	—	1,200	—	8.3	—	—	50	—	—	780	756
	07-31-52	—	1,270	—	—	—	—	74	541	—	804	—
	07-19-52	—	1,290	—	8.2	—	—	111	529	—	791	794
N3	08-26-93	18	880	—	8.4	—	—	—	—	—	—	—
	08-06-69	17.2	—	—	8.5	—	—	50	—	—	—	543
N4	08-26-93	18	820	—	7.8	—	—	—	—	—	—	—
	09-21-82	18	850	830	7.6	8.2	—	42	—	344	497	—
	06-09-82	18	560	600	8.2	8.5	—	28	—	253	362	—
	08-07-69	17.8	—	—	8.2	—	—	66	—	—	—	408
N5	08-26-93	17.5	820	—	8	—	—	—	—	—	—	—
	06-19-84	19.8	930	820	7.8	7.9	—	63	372	376	500	492
	08-06-69	16.5	—	—	7.8	—	—	82	—	385	544	—
	06-16-54	—	800	—	—	—	—	66	—	—	—	490
	08-12-53	14	770	—	8	—	—	72	—	—	490	470
	07-31-52	—	740	—	—	—	—	84	—	—	445	—
	07-19-52	—	740	—	8	—	—	104	—	—	482	483
N6	06-18-93	20.5	1,490	—	7.8	—	—	—	516	—	—	—
	10-07-89	19	1,460	1,440	7.8	8.1	.998	84	—	503	907	882
	03-10-64	21	1,630	—	8.4	—	—	63	553	—	1,070	1,050
	09-07-63	21	1,820	—	7.9	—	—	75	619	—	1,200	1,200
	07-01-63	—	1,200	—	8.5	—	—	44	539	—	756	758
	06-25-63	—	1,450	—	8.7	—	—	32	580	—	960	952
N7	03-30-93	19	1,540	—	8.1	—	—	—	512	—	—	—
	06-24-92	19	1,500	—	8.1	—	—	—	—	—	—	—
	10-03-89	19	1,560	1,620	8	8.3	.998	32	—	529	946	939

precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah

<, less than reported value; L, value determined in laboratory; ?, reported value is questionable]

Map number	Date sampled	Calcium, dis- solved (mg/L as Ca)	Magne- sium, dis- solved (mg/L as Mg)	Sodium, dis- solved (mg/L as Na)	Potas- sium, dis- solved (mg/L as K)	Bicar- bonate, field (mg/L as HCO ₃)	Car- bonate, field (mg/L as CO ₃)	Sulfate, dis- solved (mg/L as SO ₄)	Chlo- ride, dis- solved (mg/L as Cl)	Fluo- ride, dis- solved (mg/L as F)	Bro- mide, dis- solved (mg/L as Br)	Iodide, dis- solved (mg/L as I)	Silica, dis- solved (mg/L as SiO ₂)
Navajo aquifer													
N1	08-26-93	—	—	—	—	—	—	—	—	—	—	0.005	—
	06-20-84	6.7	2.7	260	13	—	—	62	57	1.1	.09	—	8.8
	06-10-82	11	3.3	350	16	—	—	67	100	1	—	—	7.5
N2	08-26-93	—	—	—	—	—	—	—	—	—	—	.014	—
	06-19-84	11	4	360	16	—	—	110	190	1.7	.55	—	10
	08-12-53	12	4.9	271	21	650	16	103	21	1.9	—	—	11
	07-31-52	21	5.2	290 K	—	660	0	96	48	1.8	—	—	13
	07-19-52	28	10	264	17	620	12	99	45	1.7	—	—	9.3
N3	08-26-93	—	—	—	—	—	—	—	—	—	—	—	—
	08-06-69	16	2.6	180	19	—	—	52	16	—	—	—	9
N4	08-26-93	—	—	—	—	—	—	—	—	—	—	—	—
	09-21-82	9.7	4.1	170	13	—	—	55	30	.6	—	—	8.5
	06-09-82	6.8	2.6	130	9.7	—	—	44	8.2	.7	—	—	8.8
	08-07-69	21	3.3	110	18	—	—	44	12	—	—	—	9.2
N5	08-26-93	—	—	—	—	—	—	—	—	—	—	—	—
	06-19-84	13	7	160	21	—	—	56	5.6	1.1	.02	—	9
	08-06-69	20	7.8	150	27	—	—	65	10	—	—	—	10
	06-16-54	13	8.2	145	11	458	0	58	11	—	—	—	—
	08-12-53	15	8.4	152	23	442	0	54	8.8	.5	—	—	10
	07-31-52	18	9.4	147 K	—	423	0	45	5	.6	—	—	11
	07-19-52	22	12	138	21	398	12	55	16	.5	—	—	9
N6	06-18-93	—	—	—	—	630	0	—	—	—	—	—	—
	10-07-89	19	8.2	290	24	—	—	230	20	1.2	.11	.006	9.4
	03-10-64	13	7.5	390 K	—	640	15	299	28	—	—	—	9.7
	09-07-63	18	7.3	418	22	760	0	297	56	1.2	—	—	10
	07-01-63	10	4.6	290 K	—	610	21	108	12	—	—	—	9.9
	06-25-63	13	0	350 K	—	650	26	176	26	—	—	—	18
N7	03-30-93	—	—	—	—	625	0	—	—	—	—	—	—
	06-24-92	—	—	—	—	—	—	—	—	—	—	—	—
	10-03-89	8.1	2.7	350	5.7	—	—	88	160	1.3	.54	.021	11

Table 7. Selected physical properties and major- and minor-chemical constituents in surface- and ground-water samples and

Map number	Date sampled	Water temperature (°C)	Specific conductance, field (μS/cm)	Specific conductance, lab (μS/cm)	pH, field (standard units)	pH, lab (standard units)	Density (g/ml at 20 °C)	Hardness, total (mg/L as CaCO ₃)	Alkalinity, field (mg/L as CaCO ₃)	Alkalinity, lab (mg/L as CaCO ₃)	Solids, sum of constituents, dissolved (mg/L)	Solids, residue at 180°C, dissolved (mg/L)
Navajo aquifer—Continued												
N8	08-27-93	20	1,720	—	7.9	—	—	—	—	—	—	—
	08-28-92	19.5	1,650	1,710	8	8.1	.999	49	466	510	986	986
	¹ 09-20-88	—	—	1,510	—	8.1	—	56	—	508	998	—
	01-31-82	—	—	1,530	8.1	—	—	46	505	505	928	944
	01-19-78	—	—	870	?	8	—	46	505	502	914	564 ?
	¹ 09-21-60	—	—	—	—	8.2	—	48	—	500	—	942
N9	¹ 09-20-88	—	—	1,390	—	8.1	—	42	—	520	912	—
	01-14-82	—	—	1,640	8.1	—	—	53	512	512	1,020	—
	01-19-78	—	—	1,450	8.1	—	—	41	512	504	954	940
	¹ 07-29-60	—	—	—	—	8.2	—	52	—	500	—	850
	¹ 08-15-59	—	—	—	—	8.2	—	40	—	514	—	657
N10	02-28-94	19	3,000	3,120	7.6	7.6	—	96	—	770	1,870	—
	03-02-93	19.5	3,110	—	7.6	—	—	—	—	—	—	—
	08-25-92	20	3,140	3,120	7.5	7.8	.999	104	766	771	1,930	1,840
	07-30-91	19	3,120	3,110	7.4	7.7	—	92	—	764	1,760	1,830
	07-18-90	19.5	3,100	3,130	7.4	7.7	—	97	—	760	1,810	1,850
	03-02-89	19	3,000	3,100	7.5	7.8	—	97	—	766	1,810	—
	03-01-88	19	3,000	—	7.4	—	—	—	—	—	—	—
	03-09-87	15	3,000	—	7.4	—	—	—	—	—	—	—
	09-02-86	21	3,120	3,050	7.7	8	—	91	—	763	1,820	—
	03-08-84	14	2,900	—	9.5	—	—	—	—	—	—	—
	06-16-83	20	3,000	3,180	7.6	7.6	—	108	—	823	1,900	—
	06-14-82	17	3,070	3,150	7.8	8	—	117	—	766	1,860	—
	07-15-60	—	3,120	—	7.8	—	—	96	690	690	2,940	1,740
N11	04-01-57	—	—	—	7.1	—	—	420	1,060	—	4,530	—
N12	03-31-93	19.5	3,400	—	7.5	—	—	—	984	—	—	—
	² 07-24-92	17	—	—	—	8.2	1.000	—	—	—	2,840	2,220
	06-26-92	20	3,480	—	7.5	—	—	—	—	—	—	—
	07-30-91	19	3,620	3,510	7.4	7.7	—	100	—	970	2,050	2,060
	07-18-90	19.5	3,520	3,470	7.4	7.7	—	95	—	958	2,060	2,120
	06-20-89	19.5	3,650	3,500	7.4	7.8	—	104	—	946	2,170	2,130
	³ 01-17-59	19.5	—	—	—	8.7	—	—	—	—	2,570	—
N13	08-25-92	17	610	620	7.8	8	.995	106	294	294	380	387
N14	03-30-93	—	—	—	—	—	1.000	—	—	—	—	—
	² 07-24-92	17	—	—	—	8.2	1.000	—	—	—	3,020	2,520
	06-23-92	19.5	3,960	—	7.5	—	—	—	—	—	—	—
	10-25-84	15.6	—	4,170	7.7	—	—	112	—	754	2,440	—
	06-06-84	15.6	4,150	4,140	7.6	7.6	—	119	805	766	2,460	2,450
	06-10-82	20	3,990	4,210	7.5	8.1	—	129	—	800	2,540	—
	³ 01-17-59	19.5	—	—	—	9	—	—	—	—	3,890	—
	05-01-56	—	—	—	7.5	—	—	152	824	—	2,390	—

precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Bicarbonate, field (mg/L as HCO ₃)	Carbonate, field (mg/L as CO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Iodide, dissolved (mg/L as I)	Silica, dissolved (mg/L as SiO ₂)
Navajo aquifer—Continued													
N8	08-27-93	—	—	—	—	—	—	—	—	—	—	—	—
	08-28-92	12	4.4	370	7.1	569	0	120	180	1.4	.47	.039	11
	¹ 09-20-88	16	4	380	—	620 L	0	125	172	—	—	—	—
	01-31-82	7	7	330	7	620	0	105	154	1.7	—	—	12
	01-19-78	10	5	340	6	610	5	92	144	.8	—	—	11
	¹ 09-21-60	—	—	—	—	—	—	210	140	—	—	—	—
N9	¹ 09-20-88	11	3	355	—	634 L	0	88	143	—	—	—	—
	01-14-82	13	5	390	9	620	0	123	158	1.7	—	—	13
	01-19-78	13	2	335	7	600	12	114	162	1.6	—	—	11
	¹ 07-29-60	—	—	330	—	—	—	130	125	—	—	—	—
	¹ 08-15-59	—	—	290	—	—	—	138	92	—	—	—	22
N10	02-28-94	23	9.3	690	15	—	—	200	460	1.4	—	—	12
	03-02-93	—	—	—	—	—	—	—	—	—	—	—	—
	08-25-92	24	10	680	14	935	0	230	500	1.4	1	.04	11
	07-30-91	21	9	660	12	—	—	180	410	1.3	1.1	—	—
	07-18-90	23	8.9	650	16	—	—	200	450	—	.82	—	—
	03-02-89	23	9.5	650	12	—	—	210	430	1.4	—	—	13
	03-01-88	—	—	—	—	—	—	—	—	—	—	—	—
	03-09-87	—	—	—	—	—	—	—	—	—	—	—	—
	09-02-86	20	10	660	13	—	—	170	470	1.3	—	—	11
	03-08-84	—	—	—	—	—	—	—	—	—	—	—	—
	06-16-83	24	11	680	15	—	—	210	450	1.5	1.1	.038	11
	06-14-82	27	12	670	14	—	—	190	480	1.4	—	—	11
	07-15-60	28	6.4	630	20	830	3	214	415	1.2	—	—	9.2
N11	04-01-57	89	48	1,300	K —	1,300	0	948	823	—	—	—	—
N12	03-31-93	—	—	—	—	1,200	0	—	—	—	—	—	—
	² 07-24-92	25	11	786	18	1,220 L	0	285	490	—	—	—	—
	06-26-92	—	—	—	—	—	—	—	—	—	—	—	—
	07-30-91	23	9.6	780	18	—	—	220	410	1.4	.79	—	—
	07-18-90	22	9	750	18	—	—	230	450	—	.84	—	—
	06-20-89	24	9.9	820	19	—	—	240	470	1.6	.82	.038	12
	³ 01-17-59	7	28	876	—	156 L	130 ?L	599	757	—	—	—	16
N13	08-25-92	22	12	95	15	359	0	46	6.8	.5	.02	.003	7.7
N14	03-30-93	—	—	—	—	—	—	—	—	—	—	.012	—
	² 07-24-92	23	9.7	891	18	1,020 L	0	315	740	—	—	—	—
	06-23-92	—	—	—	—	—	—	—	—	—	—	—	—
	10-25-84	27	10	850	18	—	—	300	760	1.3	1.9	—	10
	06-06-84	28	11	880	17	—	—	300	720	1.3	.65	—	6.7
	06-10-82	32	12	950	19	—	—	290	750	1.4	—	—	11
	³ 01-17-59	4	5	2,000	—	752 L	125 ?L	269	714	—	—	—	18
	05-01-56	8	32	1,100	K —	1,010	0	624	710	—	—	—	—

Table 7. Selected physical properties and major- and minor-chemical constituents in surface- and ground-water samples and

Map number	Date sampled	Water temperature (°C)	Specific conductance, field (μS/cm)	Specific conductance, lab (μS/cm)	pH, field (standard units)	pH, lab (standard units)	Density (g/ml at 20 °C)	Hardness, total (mg/L as CaCO ₃)	Alkalinity, field (mg/L as CaCO ₃)	Alkalinity, lab (mg/L as CaCO ₃)	Solids, sum of constituents, dissolved (mg/L)	Solids, residue at 180°C, dissolved (mg/L)
Navajo aquifer—Continued												
N15	03-30-93	—	—	—	7.7	—	—	—	578	—	—	—
	06-23-92	17	2,050	2,070	7.6	7.9	.999	106	—	555	1,300	1,270
N16	03-30-93	—	—	—	7.5	—	—	—	1,020	—	—	—
	10-26-92	19.5	3,810	—	—	—	—	—	—	—	—	—
	² 07-24-92	17	—	—	—	8.1	1.000	—	—	—	2,950	2,430
	07-30-91	19	3,920	3,800	7.4	7.6	—	101	—	992	2,230	2,300
	10-09-89	19	3,680	3,720	7.5	8.2	.999	103	—	936	2,230	2,310
N17	09-21-94	21	11,800	15,000	7.3	7.4	1.007	661	1,180	1,130	10,200	9,770
	03-10-55	16	23,400	—	7.7	—	1.011	1,370	357	—	17,800	—
	12-09-53	—	14,300	—	—	—	1.006	652	1,210	—	10,100	—
	08-17-52	21.5	5,390	—	—	—	—	217	1,890	—	3,550	—
N18	09-21-94	20	18,700	22,700	7.5	7.4	1.012	1,200	348	338	17,000	17,300
	² 09-21-94	—	—	21,500	—	7.7	1.010	1,290	—	334	17,700	17,500
	⁴ 04-29-66	—	—	26,500	—	7.8	—	1,260	—	385	19,100	18,600
N19	04-07-93	18	18,900	—	7.7	—	—	—	416	—	—	—
	06-26-92	19	17,300	—	7.7	—	—	—	—	—	—	—
	08-01-91	18.5	18,300	18,100	7.7	7.6	—	573	—	411	12,200	12,300
	07-19-90	18.8	18,400	17,500	7.5	7.5	—	551	—	398	11,100	11,900
	06-20-89	18.5	11,100	10,600	7.8	7.7	—	460	—	423	7,050	6,740
	⁴ 04-29-66	—	—	21,600	—	7.6	—	1,060	—	343	16,100	15,800
N20	11-18-92	17.5	3,200	3,290	8.3	8.4	1.000	24	708	755	2,030	2,070
N21	08-31-92	21.5	15,100	15,200	7.8	7	1.010	536	280	260	11,500	12,200
	⁵ 07-26-57	—	—	—	—	7	1.009	—	—	—	14,800	15,100
N22	09-24-94	16.5	1,470	1,470	8.7	8.6	—	11	532	—	850	888
	03-10-83	16.5	1,440	1,490	8.8	8.6	—	11	—	539	888	—
N23	04-01-93	18	8,930	—	7.3	—	—	—	516	—	—	—
	06-25-92	18.5	8,970	—	7.4	—	—	—	—	—	—	—
	07-30-91	18	9,300	9,040	7.3	7.5	—	298	—	504	6,240	6,290
	07-18-90	18.5	9,260	9,060	7.3	7.5	—	294	—	610	6,300	6,270
	06-21-89	18.5	9,460	9,100	7.3	7.6	—	286	—	503	6,350	6,380
	12-01-56	13	—	—	6	—	—	430	531	—	6,850	—
N24	06-18-93	19	2,820	2,880	8.6	8.5	.997	27	399	392	1,890	1,810
	08-25-80	—	—	2,700	8.7	—	—	24	461	461	1,660	1,690
	05-07-58	—	—	—	8.6	—	—	38	546	—	2,160	—
N25	07-31-91	17.5	13,000	12,400	8.3	8.2	—	166	—	389	8,910	8,800
	10-11-89	18	12,300	12,500	8.3	8.3	1.005	194	—	403	8,860	8,410
	⁶ 05-30-57	—	—	—	—	8.2	1.002	140	484	—	3,890	3,790

precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Bicarbonate, field (mg/L as HCO ₃)	Carbonate, field (mg/L as CO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Iodide, dissolved (mg/L as I)	Silica, dissolved (mg/L as SiO ₂)
Navajo aquifer—Continued													
N15	03-30-93	—	—	—	—	705	0	—	—	—	—	—	—
	06-23-92	20	13	440	20	—	—	300	160	1	.16	.019	8.6
N16	03-30-93	—	—	—	—	1,240	0	—	—	—	—	—	—
	10-26-92	—	—	—	—	—	—	—	—	—	—	—	—
	² 07-24-92	24	10	779	20	1,270 L	0	256	590	—	—	—	—
	07-30-91	24	9.2	840	20	—	—	230	510	1.4	1	—	—
	10-09-89	25	9.2	830	23	—	—	240	520	1.4	.85	.041	12
N17	09-21-94	150	68	3,500	42	1,440	0	2,600	3,100	.7	2.4	.29	11
	03-10-55	328	133	5,660	65	440	0	5,820	5,480	.9	—	—	11
	12-09-53	134	77	3,400	56	1,140	166 ?	2,720	2,960	.4	—	—	10
	08-17-52	54	20	1,300 K	—	2,300	0	286	685	.4	—	—	16
N18	09-21-94	290	120	5,400	42	425	0	6,000	4,900	1	3.1	.55	10
	² 09-21-94	260	103	5,840	46	354 L	26 L	5,800	5,300	—	—	—	—
	⁴ 04-29-66	338	101	6,480	23	470 L	—	4,820	6,900	1.8	—	—	—
N19	04-07-93	—	—	—	—	508	0	—	—	—	—	—	—
	06-26-92	—	—	—	—	—	—	—	—	—	—	—	—
	08-01-91	90	79	4,000	35	—	—	3,000	4,700	2.3	1.5	—	—
	07-19-90	86	76	3,600	29	—	—	2,800	4,200	—	2.4	—	—
	06-20-89	100	48	2,300	17	—	—	1,700	2,600	1.3	1.4	.21	11
	⁴ 04-29-66	273	91	5,180	94	418 L	—	5,760	4,300	2.4	—	—	—
N20	11-18-92	5.1	2.6	750	4.8	864	0	590	240	3.3	.26	.024	9.6
N21	08-31-92	120	55	3,800	26	342	0	5,400	1,900	3.3	.04	.21	9.3
	⁵ 07-26-57	75	148	4,860	—	438 L	0	6,350	3,120	—	—	—	—
N22	09-24-94	2.9	.89	330	4.4	600	24	140	52	—	—	—	—
	03-10-83	3.1	.9	340	4.3	—	—	150	52	4.7	.17	.011	9.3
N23	04-01-93	—	—	—	—	630	0	—	—	—	—	—	—
	06-25-92	—	—	—	—	—	—	—	—	—	—	—	—
	07-30-91	52	38	2,000	34	—	—	2,600	1,200	1.1	1	—	—
	07-18-90	50	38	2,000	32	—	—	2,500	1,300	—	1	—	—
	06-21-89	49	37	2,000	34	—	—	2,600	1,300	.7	.97	.16	10
	12-01-56	80	56	2,100 K	—	650	0	2,550	1,380	—	—	—	—
N24	06-18-93	5.3	3.1	750	7	462	12	630	240	4.4	.28	.034	9.5
	08-25-80	8	1	576	9	530	16	520	255	4	—	—	10
	05-07-58	7	5	700 K	—	520	72	559	301	—	—	—	—
N25	07-31-91	26	22	2,900	17	—	—	3,500	2,200	1.6	1.1	—	—
	10-11-89	33	24	2,900	18	—	—	3,600	2,000	1	14	2.7	9.2
	⁶ 05-30-57	23	20	1,250	9	566	12	1,580	726	—	—	—	—

Table 7. Selected physical properties and major- and minor-chemical constituents in surface- and ground-water samples and

Map number	Date sampled	Water temperature (°C)	Specific conductance, field (μS/cm)	Specific conductance, lab (μS/cm)	pH, field (standard units)	pH, lab (standard units)	Density (g/ml at 20 °C)	Hardness, total (mg/L as CaCO ₃)	Alkalinity, field (mg/L as CaCO ₃)	Alkalinity, lab (mg/L as CaCO ₃)	Solids, sum of constituents, dissolved (mg/L)	Solids, residue at 180°C, dissolved (mg/L)
Navajo aquifer—Continued												
N26	07-31-91	17	2,400	2,290	8.5	8.4	—	19	—	518	1,400	1,440
	² 08-20-84	—	—	2,200	—	8.4	—	—	—	—	—	1,440
N27	05-05-93	12	1,570	—	9.3	—	—	—	—	—	—	—
	06-16-89	19.5	1,410	1,350	8.6	8.6	—	10	—	475	818	792
N28	08-28-92	19.5	1,730	—	8.6	—	—	—	—	—	—	—
	⁷ 08-07-92	—	—	—	—	8.6	—	7.8	—	460	—	1,100
	07-31-91	18	1,770	1,740	8.6	8.6	—	11	—	479	1,050	1,070
	07-18-90	19.5	1,780	1,750	8.6	8.6	—	11	—	380	980	1,060
	10-06-89	19	1,690	1,730	8.7	8.8	.998	12	—	471	1,060	1,060
	² 08-20-84	—	—	1,700	—	8.6	—	—	—	—	—	1,100
N29	08-28-92	18	2,530	2,490	8.5	8.5	.998	23	458	473	1,560	1,550
	² 08-20-84	—	—	2,400	—	8.4	—	—	—	—	—	1,560
N30	⁸ 01-20-94	—	—	—	—	7.3	1.005	126	—	—	3,360	—
	04-05-93	—	—	—	7.7	—	.999	—	852	—	—	—
	06-26-92	19	4,390	—	7.6	—	—	—	—	—	—	—
	07-31-91	19	4,660	4,540	7.5	7.7	—	100	—	845	2,780	2,840
	07-19-90	19	4,550	4,580	7.5	7.7	—	109	—	813	2,810	2,840
	10-25-84	19	—	—	7.6	—	—	133	—	839	3,030	—
	04-15-83	20	4,890	4,860	7.6	7.7	—	141	—	868	3,090	—
N31	08-27-92	21	3,220	3,250	8.5	8.5	.999	22	710	753	2,160	2,120
	10-00-84	19	—	—	8.4	—	—	—	—	741	2,150	—
N32	04-05-93	17	12,700	—	7.4	—	—	—	720	—	—	—
	08-01-91	20	13,900	13,700	7.3	7.3	—	528	—	671	8,820	9,150
	10-10-89	19	14,600	14,000	7.3	7.5	1.005	507	—	650	9,110	9,010
N33	04-06-93	17.5	11,700	11,800	7.3	7.4	—	465	468	438	6,990	7,430
	08-25-89	16	11,200	10,600	9.9	9.9	—	15	—	405	6,220	6,380
	10-12-64	—	11,100	—	7.9	—	—	381	448	—	7,080	—
N34	04-02-93	16	11,800	12,400	7.4	7.6	1.003	494	478	454	7,620	7,670
	10-12-64	—	11,500	—	7.8	—	1.003	449	487	—	7,250	—
	03-18-64	—	11,200	—	7.7	—	—	469	521	—	7,460	7,330
N35	04-06-93	19	13,100	—	7.2	—	—	—	590	—	—	—
	06-25-92	18.5	13,300	—	7.1	—	—	—	—	—	—	—
	07-31-91	18	14,200	13,700	7	7.3	—	467	—	561	8,440	8,590
	07-19-90	18.5	14,500	13,700	7	7.2	—	427	—	611	8,450	8,870
	08-23-89	18.5	14,400	13,600	7.1	7.3	—	429	—	556	8,730	8,710
	03-10-55	18.5	12,000	—	7.9	—	—	567	558	—	8,620	8,640
	07-00-42	—	—	—	—	—	—	—	—	—	2,650	2,240
N36	11-18-92	22	16,500	16,600	7.9	7.8	1.007	779	264	260	11,800	11,500

precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Bicarbonate, field (mg/L as HCO ₃)	Carbonate, field (mg/L as CO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Iodide, dissolved (mg/L as I)	Silica, dissolved (mg/L as SiO ₂)
Navajo aquifer—Continued													
N26	07-31-91	5	1.4	520	3.1	—	—	400	150	4.4	0.19	—	—
	² 08-20-84	3.4	1.2	591	4.7	—	—	460	145	4.7	—	—	—
N27	05-05-93	—	—	—	—	—	—	—	—	—	—	—	—
	06-16-89	2.5	.95	310	2.8	—	—	150	53	2.9	.2	.015	10
N28	08-28-92	—	—	—	—	—	—	—	—	—	—	—	—
	⁷ 08-07-92	2	.68	150	—	—	—	360	140	3.2	—	—	—
	07-31-91	3	.79	400	2	—	—	260	95	3.6	.16	—	—
	07-18-90	3.2	.78	390	2	—	—	260	96	—	.16	—	—
	10-06-89	3.2	.81	380	2.2	—	—	280	97	3.5	.15	.01	9.2
	² 08-20-84	2.2	.9	431	3.6	—	—	265	95	3.7	—	—	—
N29	08-28-92	6.3	1.6	560	3.1	461	12	500	200	3.4	.22	.028	8.4
	² 08-20-84	4.7	1.7	636	4.8	—	—	550	185	3.8	—	—	—
N30	⁸ 01-20-94	28	14	1,030 K	—	1,070 L	0	600	618	—	—	—	—
	04-05-93	—	—	—	—	1,040	0	—	—	—	—	—	—
	06-26-92	—	—	—	—	—	—	—	—	—	—	—	—
	07-31-91	23	9.3	1,000	15	—	—	610	610	1	.55	—	—
	07-19-90	26	9.6	1,000	15	—	—	600	670	—	.63	—	—
	10-25-84	30	13	1,000	16	—	—	690	760	—	.33	—	10
	04-15-83	35	13	1,100	15	—	—	710	680	.8	.51	.075	12
N31	08-27-92	4.3	2.5	780	4.9	818	24	820	110	3.7	.12	.022	7.9
	10-00-84	4.3	3	750	4.6	—	—	820	100	—	.08	—	8
N32	04-05-93	—	—	—	—	879	0	—	—	—	—	—	—
	08-01-91	99	63	2,900	35	—	—	1,800	3,500	.9	1.5	—	—
	10-10-89	97	62	3,000	32	—	—	2,000	3,500	.5	1	.19	10
N33	04-06-93	120	37	2,400	25	571	0	1,200	2,900	.7	3.2	.052	9.6
	08-25-89	2.1	1.9	2,300	21	—	—	950	2,700	.4	3	.4	1
	10-12-64	85	41	2,500 K	—	550	0	1,360	2,810	.3	—	—	10
N34	04-02-93	130	38	2,700	24	583	0	1,200	3,200	.7	.21	.02	9.1
	10-12-64	112	41	2,600 K	—	590	0	1,280	2,960	.4	—	—	9.7
	03-18-64	112	46	2,600 K	—	640	0	1,270	3,080	—	—	—	5.3
N35	04-06-93	—	—	—	—	720	0	—	—	—	—	—	—
	06-25-92	—	—	—	—	—	—	—	—	—	—	—	—
	07-31-91	110	42	2,900	31	—	—	1,400	3,600	1.1	2.4	—	—
	07-19-90	92	43	2,900	27	—	—	1,400	3,600	—	3.2	—	—
	08-23-89	97	42	2,900	27	—	—	1,600	3,700	.4	3.4	.36	11
	03-10-55	105	74	2,940	28	680	0	1,640	3,490	.1	—	—	10
	07-00-42	17	4	761	—	878 L	19 L	865	102	—	—	—	—
N36	11-18-92	170	83	3,900	23	322	0	3,200	4,200	2.4	3.6	.27	10

Table 7. Selected physical properties and major- and minor-chemical constituents in surface- and ground-water samples and

Map number	Date sampled	Water temperature (°C)	Specific conductance, field (μS/cm)	Specific conductance, lab (μS/cm)	pH field (standard units)	pH lab (standard units)	Density (g/ml at 20 °C)	Hardness, total (mg/L as CaCO ₃)	Alkalinity, field (mg/L as CaCO ₃)	Alkalinity, lab (mg/L as CaCO ₃)	Solids, sum of constituents, dissolved (mg/L)	Solids, residue at 180°C, dissolved (mg/L)
Navajo aquifer—Continued												
N37	12-03-53	16	560	—	—	—	—	7	193	—	341	341
N38	06-15-93	16.5	840	—	9.2	—	—	—	340	—	—	—
	06-19-89	18	840	820	9	9.1	—	4	—	352	473	474
	03-11-55	16.5	850	—	9	—	—	6	355	—	499	500
N39	05-04-93	16.5	2,610	—	8.6	—	—	—	380	—	—	—
	10-26-92	17	2,720	—	—	—	—	—	—	—	—	—
	10-06-89	17.5	1,940	2,010	8.7	8.7	.998	15	—	413	1,290	1,250
N40	11-17-92	19.5	14,600	14,400	8.3	7.9	1.008	738	94	104	11,400	11,500
N41	11-16-92	21	3,120	3,250	8.3	8.2	1.000	43	392	404	2,140	2,130
N42	05-05-93	22	7,400	—	8.1	—	—	—	—	—	—	—
	06-26-92	22.5	7,250	7,400	8.1	8	1.001	120	344	359	4,860	5,180
N43	06-15-93	18.5	215	—	8.8	—	—	—	108	—	—	—
	08-24-89	20	250	240	7.8	8.7	—	51	—	105	150	145
	03-11-55	15	275	—	7.5	—	—	51	124	—	—	171
	01-20-54	16.5	—	—	—	—	—	23	337	—	—	480
N44	11-04-93	15	650	660	9.6	9.4	1.000	3	313	327	367	423
N45	04-20-94	17.5	4,360	—	—	—	—	—	—	—	—	—
	08-29-92	24	4,290	4,350	8.8	8.7	.998	54	—	413	2,840	2,870
	08-12-64	18.5	—	730	—	8.4	—	20	—	—	641	—
N46	04-01-93	20	8,340	8,390	7.9	7.9	1.002	162	464	419	5,760	5,860
N47	04-03-93	16.5	1,760	1,760	9.3	9.2	.998	17	437	429	998	1,010
N48	05-06-93	—	—	—	—	—	—	—	—	—	—	—
	06-24-92	19.5	580	590	8.4	8.4	.999	31	204	205	359	353
N49	05-06-93	—	—	—	—	—	—	—	—	—	—	—
	06-24-92	17	3,050	3,110	7.8	7.8	1.021	287	292	294	1,970	2,000
	07-30-91	17	3,180	3,130	7.7	7.8	—	273	—	287	2,030	2,030
N50	09-23-94	18	3,160	—	7.6	—	—	—	815	—	—	—
	05-04-93	—	—	—	—	—	—	—	—	—	—	—
	06-23-92	31	3,780	3,800	8.7	8.7	1.000	284	—	897	2,400	2,310
N51	06-25-92	18.5	7,370	7,490	7	7.4	1.001	307	1,580	1,680	4,600	4,900
	³ 01-19-59	21.5	—	—	—	8.6	—	—	—	—	—	5,610
N52	04-02-93	16	6,070	6,230	7.9	8	1.002	98	1,230	1,180	3,740	3,870
	³ 01-17-59	19.5	—	—	—	8.8	—	—	—	—	—	3,870

precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Bicarbonate, field (mg/L as HCO ₃)	Carbonate, field (mg/L as CO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Iodide, dissolved (mg/L as I)	Silica, dissolved (mg/L as SiO ₂)
Navajo aquifer—Continued													
N37	12-03-53	2	0.5	129	1.9	180	29	50	26	0.8	—	—	14
N38	06-15-93	—	—	—	—	341	36	—	—	—	—	—	—
	06-19-89	1	.31	190	.9	—	—	47	20	1.1	.12	.022	1.1
	03-11-55	1.3	.7	195	.8	340	45	52	21	.8	—	—	14
N39	05-04-93	—	—	—	—	430	17	—	—	—	—	—	—
	10-26-92	—	—	—	—	—	—	—	—	—	—	—	—
	10-06-89	3.9	1.2	480	2.4	—	—	410	130	2.8	.21	.015	11
N40	11-17-92	170	73	3,500	21	115	0	5,900	1,700	1.4	.17	.022	4.7
N41	11-16-93	9.8	4.1	700	4.5	430	0	1,100	100	.6	.25	.019	10
N42	05-05-93	—	—	—	—	—	—	—	—	—	—	—	—
	06-26-92	24	12	1,700	10	420	0	2,000	890	4.2	.51	.1	4.7
N43	06-15-93	—	—	—	—	113	10	—	—	—	—	—	—
	08-24-89	10	6.1	38	1.6	—	—	10	3.8	.3	.05	.003	17
	03-11-55	8.7	7.2	43 K	—	150	0	12	5	.6	—	—	19
	01-20-54	5.5	2.2	180 K	—	370	22	51	10	1.6	—	—	29
N44	11-04-93	.76	.2	150	1	253	64	8.2	3.6	1	.04	.006	13
N45	04-20-94	—	—	—	—	—	—	—	—	—	—	—	—
	08-29-92	11	6.2	990	5.5	—	—	1,200	360	2.5	.45	.066	11
	08-12-64	5.1	1.8	176 K	—	334 L	10 L	90	11	.9	—	—	12
N46	04-01-93	33	18	1,900	11	566	0	2,400	1,100	2.9	.69	.027	8.7
N47	04-03-93	2.3	2.3	380	2	411	60	97	240	.6	.25	.022	10
N48	05-06-93	—	—	—	—	—	—	—	—	—	—	—	—
	06-24-92	7.4	2.8	120	3.3	236	6	71	19	.3	.03	.003	12
N49	05-06-93	—	—	—	—	—	—	—	—	—	—	—	—
	06-24-92	60	32	580	23	356	0	720	360	<.1	.31	.052	10
	07-30-91	56	31	570	21	—	—	780	390	.5	.29	—	—
N50	09-23-94	—	—	—	—	995	0	—	—	—	—	—	—
	05-04-93	—	—	—	—	—	—	—	—	—	—	—	—
	06-23-92	60	32	840	25	—	—	360	520	1.6	.85	.05	13
N51	06-25-92	64	34	1,700	40	1,930	0	700	1,100	.3	1.1	.062	5.4
	³ 01-19-59	7	36	1,840	—	1,310 L	254 ?L	883	1,240	—	—	—	21
N52	04-02-93	25	7.7	1,400	17	1,500	0	430	1,100	1.1	3.4	.012	8.4
	³ 01-17-59	13	3	1,350	—	600 L	168 ?L	455	1,240	—	—	—	19

Table 7. Selected physical properties and major- and minor-chemical constituents in surface- and ground-water samples and

Map number	Date sampled	Water temperature (°C)	Specific conductance, field (μS/cm)	Specific conductance, lab (μS/cm)	pH, field (standard units)	pH, lab (standard units)	Density (g/ml at 20 °C)	Hardness, total (mg/L as CaCO ₃)	Alkalinity, field (mg/L as CaCO ₃)	Alkalinity, lab (mg/L as CaCO ₃)	Solids, sum of constituents, dissolved (mg/L)	Solids, residue at 180°C, dissolved (mg/L)
Navajo aquifer—Continued												
N53	08-26-92	18	420	425	9.1	8.3	0.996	16	165	168	261	260
N54	09-23-94	17.5	5,970	6,770	7.3	7.4	—	706	480	438	4,470	4,380
N55	11-20-92	15	4,460	—	—	—	—	—	—	—	—	—
	³ 01-19-59	21.5	—	—	—	9.5	—	—	—	—	—	5,510
N56	09-23-94	20	3,680	3,780	8.6	8.5	—	85	766	791	2,510	2,560
Alluvial aquifer												
A1	06-17-93	20	4,980	4,780	7.6	7.7	1.001	776	236	223	3,910	3,800
A2	⁸ 01-20-94	—	—	—	—	7.5	1.003	28	—	—	1,170	—
	⁹ 09-23-93	15	—	1,050	—	7.2	—	400	—	185	686	770
	08-27-92	16.5	830	760	7.6	7.9	.995	292	167	150	518	543
A3	04-05-93	15	3,350	—	8.5	—	—	—	670	—	—	—
	10-09-89	17	3,290	3,340	8.4	8.5	.999	28	—	631	2,280	2,290
Dakota aquifer												
D1	06-16-93	20	3,640	3,600	7.8	8	.998	559	482	501	2,550	2,650
Morrison aquifer												
M1	06-17-93	18	3,420	3,310	8.1	8.2	.999	25	616	595	2,260	2,230
M2	08-26-92	17.5	4,600	4,530	8.1	8.2	1.006	45	570	568	3,160	3,200
M3	11-05-93	4	1,180	1,200	8.3	8.1	1.000	94	319	332	738	752
Upper Paleozoic aquifer												
UPZ1	04-17-94	27	9,030	9,520	8.7	7.3	1.005	241	—	246	6,760	7,260
UPZ2	04-21-94	30	17,400	20,600	7.9	7.9	1.009	1,700	—	207	12,900	14,200
UPZ3	04-21-94	23	4,260	4,610	8.1	7.9	1.006	239	—	372	2,540	2,520
UPZ4	04-19-94	32	32,200	39,000	7.1	7.2	1.018	4,680	—	309	25,500	27,600
	¹⁰ 03-11-92	23	—	—	—	7.1	1.018	—	—	—	20,300	—
	¹⁰ 07-26-90	23	—	—	—	7.3	1.018	—	—	—	21,600	—
UPZ5	⁶ 07-23-60	—	—	—	—	7.8	1.016	—	—	—	23,600	—

precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Bicarbonate, field (mg/L as HCO ₃)	Carbonate, field (mg/L as CO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Iodide, dissolved (mg/L as I)	Silica, dissolved (mg/L as SiO ₂)
Navajo aquifer—Continued													
N53	08-26-92	4.2	1.3	90	2.5	164	18	46	6.9	.2	<.01	.001	11
N54	09-23-94	140	85	1,300	39	586	0	1,300	1,300	—	—	—	9.9
N55	11-20-92	—	—	—	—	—	—	—	—	—	—	—	—
	³ 01-19-59	294	26	1,420	—	1,860	L 204	?L 453	1,210	—	—	—	9
N56	09-23-94	29	2.7	900	5.5	886	24	1,000	100	—	—	—	9
Alluvial aquifer													
A1	06-17-93	210	59	1,100	12	288	0	2,300	66	.9	.23	.005	11
A2	⁸ 01-20-94	6	3	344	K —	454	L 0	284	77	—	—	—	—
	⁹ 09-23-93	93	41	67	7.4	226	0	335	32	.33	—	—	—
	08-27-92	80	22	56	2.7	204	0	230	16	.4	.04	.008	9
A3	04-05-93	—	—	—	—	744	36	—	—	—	—	—	—
	10-09-89	5.5	3.3	780	4.5	—	—	1,000	100	3.7	.11	.011	8.6
Dakota aquifer													
D1	06-16-93	74	90	670	9.3	588	0	1,300	100	1.1	.52	.009	14
Morrison aquifer													
M1	06-17-93	6.3	1.7	840	4.2	752	0	970	55	1.3	.21	.01	9.9
M2	08-26-92	8.4	5.3	1,100	6.7	696	0	1,500	190	2.7	.24	.019	7.2
M3	11-05-93	28	5.5	230	1.3	390	0	250	17	.8	.21	.005	12
Upper Paleozoic aquifer													
UPZ1	04-17-94	75	11	2,100	1.9	—	—	3,400	1,000	1.6	0.79	0.2	17
UPZ2	04-21-94	480	120	3,400	1.5	—	—	2,700	6,000	.5	9.7	.53	12
UPZ3	04-21-94	67	16	860	2.5	—	—	150	1,200	1.5	2.2	.14	11
UPZ4	04-19-94	1,400	260	7,900	4.4	—	—	610	15,000	.6	31	1.7	12
	¹⁰ 03-11-92	760	188	6,760	—	367	L 0	181	12,000	—	—	—	—
	¹⁰ 07-26-90	663	135	7,400	—	390	L 0	600	12,400	—	—	—	—
UPZ5	07-23-60	439	136	9,100	26	428	L 0	892	12,800	—	—	—	—

Table 7. Selected physical properties and major- and minor-chemical constituents in surface- and ground-water samples and

Map number	Date sampled	Water temperature (°C)	Specific conductance, field (μS/cm)	Specific conductance, lab (μS/cm)	pH, field (standard units)	pH, lab (standard units)	Density (g/ml at 20 °C)	Hardness, total (mg/L as CaCO ₃)	Alkalinity, field (mg/L as CaCO ₃)	Alkalinity, lab (mg/L as CaCO ₃)	Solids, sum of constituents, dissolved (mg/L)	Solids, residue at 180°C, dissolved (mg/L)
Oil-field brine												
PRD1	06-16-93	—	105,000	—	7.3	—	—	—	—	—	—	—
	06-22-89	36	105,000	101,000	7.1	6.7	—	19,800	—	72	78,800	84,700
PRD1A	11-05-93	—	85,600	103,000	7	7.1	—	21,800	—	93	82,800	89,000
PRD2	11-20-92	13	87,000	99,500	6	6.4	1.051	17,700	—	643	71,700	72,100
PRD3	06-16-93	—	172,000	—	6.7	—	—	—	—	—	—	—
	10-09-89	24	171,000	179,000	6.8	6.6	1.116	25,800	—	75	174,000	184,000
PRD4	08-31-92	31.5	105,000	105,000	7	6.7	1.058	20,800	—	158	82,400	95,000
PRD4A	11-05-93	—	80,600	100,000	7.1	6.9	—	21,400	—	126	88,700	86,100
PRD5	08-25-93	27	69,000	90,400	7.3	7.4	1.047	15,300	—	84	75,900	75,000
Non-oil-field brine												
¹¹ 12E	09-07-94	—	—	—	—	—	—	—	—	—	—	—
¹¹ 8E	09-07-94	—	—	—	—	—	—	—	—	—	—	—
¹¹ 4E	09-07-94	—	—	—	—	—	—	—	—	—	—	—
Surface water												
SW1	04-20-94	16	3,260	3,600	8.3	—	—	—	—	—	—	—
SW2	07-22-93	23	620	600	8.4	8.5	—	259	118	121	404	397
	05-19-93	15.5	380	380	8.2	—	—	—	86	—	—	—
	03-24-93	10	520	520	8.2	7.9	—	198	108	111	328	339
	11-23-92	5.5	870	860	8.5	8.2	—	312	142	143	567	595
Precipitation												
P1	03-03-94	—	—	9	—	—	—	—	—	—	—	—
P2	03-03-94	—	—	7	—	—	—	—	—	—	—	—

¹Analysis by El Paso Natural Gas Laboratory, Farmington, New Mexico.²Analysis by CDS Laboratories, Durango, Colorado.³Analysis reported in Barnes (unpub. data, 1959).⁴Analysis by Area Soils Laboratory, Gallup, New Mexico.⁵Analysis by Core Laboratories, Dallas, Texas.

precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Bicarbonate, field (mg/L as HCO ₃)	Carbonate, field (mg/L as CO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Iodide, dissolved (mg/L as I)	Silica, dissolved (mg/L as SiO ₂)
Oil-field brine													
PRD1	06-16-93	—	—	—	—	—	—	—	—	—	—	—	—
	06-22-89	5,700	1,300	22,000	430	—	—	830	48,000	1.6	280	17	25
PRD1A	11-05-93	6,400	1,400	20,000	410	—	—	1,100	53,000	—	380	23	—
PRD2	11-20-92	5,000	1,200	20,000	360	—	—	240	44,000	3	270	18	27
PRD3	06-16-93	—	—	—	—	—	—	—	—	—	—	—	—
	10-09-89	7,700	1,600	52,000	1,100	—	—	1,100	110,000	.9	400	47	5
PRD4	08-31-92	5,800	1,500	24,000	440	—	—	2,000	48,000	14	270	17	23
PRD4A	11-05-93	6,100	1,500	25,000	350	—	—	1,200	54,000	—	480	24	—
PRD5	08-25-93	4,400	1,000	20,000	320	—	—	1,700	48,000	9.7	200	11	16
Non-oil-field brine													
¹¹ 12E	09-07-94	—	—	—	—	—	—	—	148,000	—	87	—	—
¹¹ 8E	09-07-94	—	—	—	—	—	—	—	151,000	—	86	—	—
¹¹ 4E	09-07-94	—	—	—	—	—	—	—	149,000	—	84	—	—
Surface water													
SW1	04-20-94	—	—	—	—	—	—	1,500	270	—	2	.032	—
SW2	07-22-93	77	16	40	2.1	130	7	180	13	.3	.02	.003	3.1
	05-19-93	—	—	—	—	105	0	—	—	—	<.01	.003	—
	03-24-93	51	17	31	2.7	130	0	140	10	.2	.02	.003	10
	11-23-92	83	25	58	2.8	158	7	290	16	.3	.03	.002	5.4
Precipitation													
P1	03-03-94	—	—	—	—	—	—	—	.2	—	<.01	.001	—
P2	03-03-94	—	—	—	—	—	—	—	.4	—	<.01	.001	—

⁶Analysis by Continental Oil Company, Ponca City, Oklahoma.⁷Analysis by Westech Laboratories, Phoenix, Arizona.⁸Analysis by Martin Water Laboratories, Midland, Texas.⁹Analysis by Intermountain Laboratories, Farmington, New Mexico.¹⁰Analysis by Welchem Inc., Houston, Texas.¹¹Data collected from sites northeast of the study area in Paradox Valley, Colorado. Data compiled from Rosenbauer and others (1992).

Table 8. Selected trace-element constituents and isotope values in surface- and ground-water samples and precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah

[µg/L, micrograms per liter; mg/L, milligrams per liter; permil, per thousand; —, no data; <, less than reported value; T, reported as total concentration; ?, reported value is questionable]

Map number: Refer to table 1 and figure 10.

Map number	Date sampled	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Total organic carbon (mg/L as C)	Deuterium-18 (permil)	Deuterium-25 (permil)	Sulfur-34 (permil)	Strontium-87 (permil)
Navajo aquifer													
N1	08-26-93	—	—	—	—	—	—	<1	0.1	—	—	-0.1	2.02
	06-20-84	64	850	42	480	8	620	—	.2	-15.40	-114	-.2	—
N2	08-26-93	—	—	—	—	—	—	1.3	.2	—	—	2.3	1.48
	06-19-84	38	650	86	560	8	2	—	.2	-15.00	-112	0	—
	08-12-53	—	28	50	—	—	—	—	—	—	—	—	—
	07-19-52	—	30	90	—	—	—	—	—	—	—	—	—
N3	08-06-69	—	—	45	—	—	—	—	—	—	—	—	—
N4	09-21-82	100 T	—	150 T	340 T	10 T	700 T	—	—	—	—	—	—
	08-07-69	—	—	55	—	—	—	—	—	—	—	—	—
N5	06-19-84	56	460	4	300	9	1,100	—	—	-14.70	-111	-3.5	—
	08-12-53	—	39	50	—	—	—	—	—	—	—	—	—
	07-19-52	—	290	50	—	—	—	—	—	—	—	—	—
N6	06-18-93	—	—	—	390	20	—	—	.2	—	—	—	—
	10-07-89	27	280	900	—	—	2,300	<1	—	-15.10	-113	7.5	1.71
	09-07-63	—	230	130	—	—	—	—	—	—	—	—	—
N7	03-30-93	—	—	—	510	20	—	—	—	—	—	—	—
	06-24-92	—	—	—	—	—	—	—	.5	-15.30	-114	—	—
	10-03-89	34	680	160	—	—	750	2	—	—	—	6.2	1.42
N8	08-27-93	—	—	—	—	20	—	—	—	—	—	—	—
	08-28-92	43	1,100	200	565	—	1,100	2.3	.2	-15.20	-113	4.8	1.35
	01-31-82	—	1,200	—	—	15 T	—	—	—	—	—	—	—
	01-19-78	70	600	740	—	77	—	—	—	—	—	—	—
N9	01-14-82	—	1,180	310 T	—	20 T	—	—	—	—	—	—	—
	01-19-78	40	700	67	—	48	—	—	—	—	—	—	—
N10	02-28-94	—	1,500	80	—	—	—	—	—	—	—	—	—
	08-25-92	<100	1,500	790	911	26	2,500	10	.1	-14.75	-111	6.6	.97
	07-30-91	—	—	—	—	—	2,600	—	—	—	—	—	—
	07-18-90	—	—	—	—	—	2,400	—	—	—	—	—	—
	03-02-89	—	1,400	830	—	20	—	—	—	—	—	—	—
	09-02-86	—	1,500	4,400	—	150	—	—	—	—	—	—	—
	06-16-83	100 T	—	960 T	970 T	20 T	2,100 T	—	—	—	—	—	—
	07-15-60	—	1,400	570	—	—	—	—	—	—	—	—	—

Table 8. Selected trace-element constituents and isotope values in surface- and ground-water samples and precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Total organic carbon (mg/L as C)	Deuterium-18 (permil)	Deuterium-26 (permil)	Sulfur-34 (permil)	Strontium-87 (permil)
Navajo aquifer—Continued													
N12	03-31-93	—	—	—	960	20	—	—	—	—	—	—	—
	06-26-92	—	—	—	—	—	—	—	<.1	—	—	—	—
	07-30-91	—	—	—	—	—	2,700	—	—	—	—	—	—
	07-18-90	—	—	—	—	—	2,400	—	—	—	—	—	—
	06-20-89	<100	1,600	380	—	—	2,600	10	—	-14.60	-110	7.6	1.69
N13	08-25-92	51	200	100	131	17	1,500	<1	.3	-15.35	-115	-7.6	1.85
N14	03-30-93	—	—	—	—	—	—	14	—	—	—	—	—
	06-23-92	—	—	—	—	—	—	—	.5	—	—	—	1.65
	10-25-84	<100	1,400	470	1,100	20	3,100	—	.1	-14.60	-110	9.7	—
N15	03-30-93	—	—	—	410	10	—	—	—	—	—	—	—
	06-23-92	<100	480	110	—	—	1,800	2.1	.2	-14.80	-112	7.0	1.18
N16	03-30-93	—	—	—	1,100	10	—	—	—	—	—	—	—
	10-26-92	—	—	—	—	—	—	—	2.8	—	—	—	—
N16	07-30-91	—	—	—	—	—	2,700	—	—	—	—	—	—
	10-09-89	<100	1,700	260	—	—	2,700	9	—	-14.60	-107	7.7	1.75
N17	09-21-94	<100	5,400	6,800	2,000	310	5,900	—	12	-11.76	-94.6	—	1.27
	03-10-55	—	—	40	42,000 ?	20	—	—	—	—	—	—	—
N18	09-21-94	<100	7,600	1,600	2,300	130	11,000	—	2.3	-8.78	-81.3	—	.93
	¹ 04-29-66	—	8,150	—	—	—	—	—	—	—	—	—	—
N19	04-07-93	—	—	—	3,200	70	—	—	—	—	—	—	—
	06-26-92	—	—	—	—	—	—	—	.5	—	—	—	.78
	08-01-91	—	—	—	—	—	20,000	—	—	—	—	—	—
	07-19-90	—	—	—	—	—	20,000	—	—	—	—	—	.71
	06-20-89	<100	2,800	100	—	—	11,000	20	—	-12.29	-97.9	9.8	.79
	¹ 04-29-66	—	6,450	70	—	—	—	—	—	—	—	—	—
N20	11-18-92	<100	450	80	510	<10	650	2.8	1.6	-13.65	-96.2	5.8	.10
N21	08-31-92	<100	3,800	880	2,090	111	9,000	49	45	-11.30	-89.5	10.3	.52
N22	09-24-94	—	—	130	210	19	310	—	—	—	—	—	1.20
N23	04-01-93	—	—	—	1,400	140	—	—	—	—	—	—	—
	06-25-92	—	—	—	—	—	—	—	.1	—	—	—	1.24
	07-30-91	—	—	—	—	—	10,000	—	—	—	—	—	—
	07-18-90	—	—	—	—	—	11,000	—	—	—	—	—	—
	06-21-89	<100	310	2,500	—	—	10,000	38	—	-12.15	-93.5	9.7	1.10
N24	06-18-93	<100	170	60	380	20	550	3.9	3.2	-12.90	-95.5	8.8	.41
	08-25-80	—	205	240 T	—	—	—	—	—	—	—	—	—

Table 8. Selected trace-element constituents and isotope values in surface- and ground-water samples and precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Total organic carbon (mg/L as C)	Deuterium-18 (permil)	Deuterium-26 (permil)	Sulfur-34 (permil)	Strontium-87 (permil)
Navajo aquifer—Continued													
N25	07-31-91	—	—	—	—	—	9,300	—	—	—	—	—	—
	10-11-89	<100	1,000	40	—	—	11,000	11	—	-11.65	-93.5	9.5	.13
	² 05-30-57	—	—	800	—	—	—	—	—	—	—	—	—
N26	07-31-91	—	—	—	—	—	540	—	—	—	—	—	—
	³ 08-20-84	54	—	560	—	—	—	—	—	—	—	—	—
N27	05-05-93	—	—	—	190	10	—	—	9.9	—	—	—	.38
	06-16-89	3	890	180	—	—	240	<1	—	-13.70	-106	1.6	—
N28	08-28-92	—	—	—	—	—	—	—	.2	—	—	—	.16
	⁴ 08-07-92	<50	—	19,000 ?	—	150	—	—	—	—	—	—	—
	07-31-91	—	—	—	—	—	250	—	—	—	—	—	—
	07-18-90	—	—	—	—	—	250	—	—	—	—	—	—
	10-06-89	13	1,100	69	—	—	250	<1	—	-14.20	-106	4.7	—
	³ 08-20-84	13	—	270	—	—	—	—	—	—	—	—	—
N29	08-28-92	<100	1,100	<10	311	16	800	2	.2	-14.10	-106	6.4	.17
	³ 08-20-84	20	—	120	—	—	—	—	—	—	—	—	—
N30	04-05-93	—	—	—	—	—	—	8.9	—	—	—	—	—
	06-26-92	—	—	—	—	—	—	—	.1	—	—	—	.99
	07-31-91	—	—	—	—	—	3,700	—	—	—	—	—	—
	07-19-90	—	—	—	—	—	3,600	—	—	—	—	—	—
	10-25-84	<100	160	1,600	820	50	3,800	—	—	-13.30	-104	6.1	—
N31	08-27-92	<100	350	160	510	22	640	400	.2	-13.60	-96.5	9.3	-.01
	10-00-84	<100	350	70	490	20	640	—	—	-13.50	-98.5	6.1	—
N32	04-05-93	—	—	—	2,200	190	—	—	5.5	—	—	—	—
	08-01-91	—	—	—	—	—	19,000	—	—	—	—	—	—
	10-10-89	<100	230	11,000	—	—	8,500	12	—	-12.25	-95.4	10.1	.63
N33	04-06-93	<100	230	2,000	1,800	70	11,000	83	1.1	—	—	11.0	.51
	08-25-89	<100	200	30	—	—	1,200	47	—	-12.80	-99.5	21.8	.59
N34	04-02-93	<100	240	2,600	1,900	80	11,000	84	2.3	-12.86	-98.1	11.2	.54
N35	04-06-93	—	—	—	2,100	40	—	—	—	—	—	—	—
	06-25-92	—	—	—	—	—	—	—	.1	—	—	—	—
	07-31-91	—	—	—	—	—	17,000	—	—	—	—	—	—
	07-19-90	—	—	—	—	—	18,000	—	—	—	—	—	—
	08-23-89	<100	430	1,400	—	—	12,000	37	—	-12.55	-96.0	9.8	.48
N36	11-18-92	<100	2,400	280	2,000	74	11,000	98	.3	-12.30	-93.4	9.3	.38
N38	06-15-93	—	—	—	90	10	—	—	1.2	—	—	—	.03
	06-19-89	6	200	30	—	—	53	<1	—	-15.35	-120	2.3	—
	03-11-55	—	—	10 T	—	—	—	—	—	—	—	—	—

Table 8. Selected trace-element constituents and isotope values in surface- and ground-water samples and precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Total organic carbon (mg/L as C)	Deuterium-18 (permil)	Deuterium-26 (permil)	Sulfur-34 (permil)	Strontium-87 (permil)
Navajo aquifer—Continued													
N39	05-04-93	—	—	—	300	20	—	—	—	—	—	—	—
	10-26-92	—	—	—	—	—	—	—	3.4	—	—	—	—
	10-06-89	<100	1,200	360	—	—	400	1	—	-13.65	-106	6.6	.08
N40	11-17-92	<100	420	50	400	180	11,000	34	.1	-13.07	-99.8	7.5	-.24
N41	11-16-92	<100	240	<10	710	<10	1,100	2.4	.1	-14.09	-102	8.8	.06
N42	05-05-93	—	—	—	740	50	—	—	—	—	—	—	—
	06-26-92	<100	240	250	—	—	9,100	19	<.1	-12.40	-95.0	9.6	.35
N43	06-15-93	—	—	—	20	<10	—	—	.1	—	—	—	-.85
	08-24-89	31	50	110	—	—	450	17	—	-9.50	-78.0	2.6	-.80
N44	11-04-93	4	110	13	10	1	38	270	.2	-13.58	-105	2.5	-.79
N45	04-20-94	—	—	—	—	—	—	—	—	-12.65	-99.8	—	—
	08-29-92	<100	470	30	640	<10	1,300	7.7	.6	—	—	11.7	-.63
N46	04-01-93	<100	2,500	30	1,200	30	4,800	34	.4	-12.19	-94.1	10.6	.30
N47	04-03-93	120	200	10	140	3	1,100	3	1.2	-14.77	-107	6.1	.56
N48	05-06-93	—	—	—	110	10	—	—	—	—	—	—	—
	06-24-92	45	100	37	—	—	610	<1	.1	-15.20	-112	-4.1	1.47
N49	05-06-93	—	—	—	540	130	—	—	—	—	—	—	—
	06-24-92	<100	410	620	—	—	4,800	4.5	.4	-15.55	-116	8.9	1.14
	07-30-91	—	—	—	—	—	5,000	—	—	—	—	—	—
N50	05-04-93	—	—	—	850	40	—	—	—	—	—	—	—
	06-23-92	<100	1,800	50	—	—	2,500	12	3.1	-14.00	-107	8.7	1.41
N51	06-25-92	<100	1,400	1,500	—	—	5,900	41	.2	-13.80	-103	9.7	1.54
N52	04-02-93	<100	1,900	30	1,400	70	3,800	32	1.5	-14.33	-108	15.4	1.45
N53	08-26-92	21	40	37	82	13	180	1.6	1.6	-15.30	-112	-13.5	.11
N54	09-23-94	—	—	90	—	—	5,600	—	—	—	—	—	.99
N56	09-23-94	—	—	10	—	—	970	—	—	—	—	—	.27
Alluvial aquifer													
A1	06-17-93	<100	70	30	140	90	7,300	<1	2	-11.26	-86.7	-15.7	-.59
A2	08-27-92	36	70	44	38	230	1,100	2	1.9	-13.15	-96.0	-12.4	.10
A3	04-05-93	—	—	—	560	10	—	—	3.1	—	—	—	—
	10-09-89	<100	400	30	—	—	910	1	—	-13.70	-97.0	7.2	-.11

Table 8. Selected trace-element constituents and isotope values in surface- and ground-water samples and precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Total organic carbon (mg/L as C)	Deuterium-18 (permil)	Deuterium-26 (permil)	Sulfur-34 (permil)	Strontium-87 (permil)
Dakota aquifer													
D1	06-16-93	<100	120	<10	370	10	3,200	3.2	1.9	-12.89	-96.5	7.0	-.45
Morrison aquifer													
M1	06-17-93	<100	520	90	550	10	2,100	<1	.4	-13.70	-105	-4.4	-.49
M2	08-26-92	<100	260	10	663	<10	1,600	2.8	.2	-13.30	-99.0	7.7	-.07
M3	11-05-93	85	100	5	46	6	940	12	—	-9.63	-82.4	-5.1	—
Upper Paleozoic aquifer													
UPZ1	04-17-94	<100	1,200	210	340	80	7,000	29	240	-11.84	-93.5	12.1	1.10
UPZ2	04-21-94	<100	850	160	1,200	210	10,000	170	15	-11.91	-94.6	10.3	.82
UPZ3	04-21-94	<100	700	510	530	60	5,100	8.4	2.8	-15.12	-113	6.8	.94
UPZ4	04-19-94	<100	1,500	2,100	2,600	800	100,000	420	17	-12.26	-97.3	10.7	.34
	⁵ 03-11-92	—	—	—	—	—	54,000	—	—	—	—	—	—
	⁵ 07-26-90	—	—	3,000	—	—	51,000	—	—	—	—	—	—
Oil-field brine													
PRD1	06-16-93	—	—	—	2,500	—	—	—	6.5	—	—	—	—
	06-22-89	1,100	32,000	850	—	—	180,000	340	—	-6.70	-79.0	19.0	-.82
PRD1A	11-05-93	—	—	—	—	—	—	—	—	-6.46	-71.6	—	—
PRD2	11-20-92	400	37,000	3,800	2,000	276	200,000	2,500	20	-7.51	-72.1	19.7	-1.06
PRD3	06-16-93	—	—	—	5,700	510	—	—	180	—	—	—	—
	10-09-89	<1,000	120,000	1,400	—	—	5,500	2,400	—	2.19	-42.0	7.8	-1.06
PRD4	08-31-92	100	39,000	180	2,490	321	160,000	400	5.2	-5.60	-68.5	22.5	-1.03
PRD4A	11-05-93	—	—	—	—	—	—	—	—	-6.21	-70.4	—	—
PRD5	08-25-93	400	28,000	130	2,900	70	140,000	980	24	-7.58	-72.3	21.5	-.79
Surface water													
SW1	04-20-94	—	—	—	—	—	—	—	—	-10.55	-88.3	—	—
SW2	07-22-93	88	—	<3	32	—	890	<1	—	-13.78	-102	-3.2	—
	05-19-93	—	—	—	—	—	—	—	—	-14.61	-106	—	—
	03-24-93	91	—	15	20	—	640	<6	—	-13.63	-98.4	—	—
	11-23-92	64	—	<3	38	—	1,200	<6	—	-12.57	-92.7	—	—

Table 8. Selected trace-element constituents and isotope values in surface- and ground-water samples and precipitation samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah—Continued

Map number	Date sampled	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Total organic carbon (mg/L as C)	Deuterium-18 (permil)	Deuterium-26 (permil)	Deuterium-34 (permil)	Deuterium-87 (permil)
Precipitation													
P1	03-03-94	—	—	—	—	—	—	—	—	-16.69	-122	—	—
P2	03-03-94	—	—	—	—	—	—	—	—	-15.76	-115	—	—

¹Analysis by Area Soils Laboratory, Gallup, New Mexico.

²Analysis by Continental Oil Company, Ponca City, Oklahoma.

³Analysis by CDS Laboratories, Durango, Colorado.

⁴Analysis by Westech Laboratories, Phoenix, Arizona.

⁵Analysis by Welch Inc., Houston, Texas.

chloride sulfate, and sodium sulfate chloride type (pl. 1). Consequently, water from the upper Paleozoic aquifer that mixes with water in the Navajo aquifer or water that is derived from localized dissolution of evaporites in the Navajo aquifer would contain increased concentrations of sulfate and chloride relative to bicarbonate.

Saline water from selected wells in the Morrison aquifer and in alluvium was generally characterized as sodium sulfate bicarbonate type (pl. 1). Water from a saline spring in the Dakota Sandstone (D1) and a well in alluvium (A1) however, was classified as sodium sulfate type (pl. 1). The high concentration of sodium sulfate in water from well A1 and spring D1 might have been derived from dissolution of sulfate minerals in the Mancos Shale, which is locally present overlying the Dakota Sandstone in this area. Water from well A2, yielding from alluvium along the floodplain of the San Juan River, was characterized as calcium sodium sulfate type. Salinity in water from wells in unconfined aquifers overlying the Navajo aquifer where chloride is not a major constituent may be explained by in situ water-rock interactions, as discussed previously, or from downward migration of mineralized water from overlying strata, rather than mixing with saline water moving upward from other formations.

Trace- and minor-element constituents sampled in water from the Navajo aquifer include barium, boron, bromide, iodide, iron, lithium, manganese, strontium, and vanadium (tables 7 and 8). Boron, lithium, and strontium are generally present in high con-

centrations in very saline water such as brines and also are the major trace elements in saline water from the Navajo aquifer. Maximum concentrations of these elements were: boron, in well N18, 7,600 µg/L; strontium, in well N19, 20,000 µg/L; and lithium, in well N19, 3,200 µg/L. High concentrations of iron in water from some wells indicates corrosion of casings is possibly taking place. Water from well N32, discharging around a plugged and abandoned marker, has a dissolved-solids concentration of about 9,000 mg/L and an iron concentration of 11,000 µg/L.

Total organic carbon in water from wells in the Navajo aquifer ranged from less than 0.1 to 45 mg/L (table 8). Produced water from the Paradox Formation had a maximum total organic carbon concentration of 180 mg/L, and saline water from the upper Paleozoic aquifer had a maximum concentration of 240 mg/L. Generally, total organic carbon concentrations in ground-water systems with low dissolved-solids concentrations are only several tenths of a milligram per liter. Water containing total organic carbon concentrations more than several milligrams per liter indicates the presence of unoxidized organic material that may be enriched in bromide and iodide. Water from well N21 had a total organic carbon concentration of 45 mg/L, substantially more than the concentrations in water of most oil-field brine samples collected during the study. Organic chemical additives injected into this well to inhibit corrosion of the well casing are a possible cause of this anomalous total organic carbon value.

Variations in Salinity of Water in the Navajo Aquifer

Dissolved-solids concentrations in water from most wells completed in the Navajo aquifer in and near the Greater Aneth Oil Field varied less than 10 percent in the 40 years since most of the wells were drilled (fig. 12). Changes in dissolved-solids concentrations throughout time, however, have been noted in water from selected wells (Avery, 1986; Spangler, 1992). Increases of greater than 50 percent in specific-conductance values or dissolved-solids concentrations have been documented in wells N4, N17, N35, and N45 (fig. 12). Water from well N35 had a reported dissolved-solids concentration of about 2,200 mg/L in 1942, when the well was drilled and a dissolved-solids concentration of about 8,600 mg/L in 1955, 13 years later. Salinity of water from this well during the last 36 years (1956-92), on the basis of available data, however, has remained relatively stable (table 7). The specific-conductance value of water from well N45 was 730 $\mu\text{S}/\text{cm}$ several days after the well was completed in 1964 and 4,350 $\mu\text{S}/\text{cm}$ in 1992, indicating an increase of about 240 percent and a change from freshwater (sodium bicarbonate) to almost moderately saline water (sodium sulfate chloride) in less than 30 years. The rate of change in salinity cannot be determined from the available data; thus, salinity may have increased to the present value within a short time after pumping of the well began or may have increased gradually during the 30 years. "Apparent" increases in salinity during the study (1989-94) were documented in wells N19 (discussed below) and N39. Water from well N39 had a specific-conductance value of 1,940 $\mu\text{S}/\text{cm}$ in 1989 and a value of about 2,700 $\mu\text{S}/\text{cm}$ in 1992.

Decreases in salinity also have been documented in water from three wells (fig. 12). Water from well N1 had a specific-conductance value of 1,570 $\mu\text{S}/\text{cm}$ in 1982 and 1,180 $\mu\text{S}/\text{cm}$ only 2 years later. Water from well N18 had a reported specific-conductance value of about 26,500 $\mu\text{S}/\text{cm}$ when the well was drilled in 1966, and a value of 22,700 $\mu\text{S}/\text{cm}$ in 1994, a 15-percent difference in 28 years. Water from well N43 had a specific-conductance value of 275 $\mu\text{S}/\text{cm}$ in 1955; during the study, an "apparent" decrease from 250 to 215 $\mu\text{S}/\text{cm}$ was noted.

Water from several wells has shown "apparent" increases and decreases in salinity throughout time (table 7). Water from well N17 showed large increases in salinity during the 3 years after the well was completed and also indicated that high concentrations of

dissolved solids were present in some parts of the Navajo aquifer prior to discovery and development of the Greater Aneth Oil Field in the late 1950s. Water from well N17 had a specific-conductance value of about 5,400 $\mu\text{S}/\text{cm}$ (3,550 mg/L) in 1952, when the well was drilled, 14,300 $\mu\text{S}/\text{cm}$ (10,100 mg/L) in 1953, and 23,400 $\mu\text{S}/\text{cm}$ (17,800 mg/L) in 1955, an increase in dissolved-solids concentration of about 14,000 mg/L during 3 years. Water sampled from the well in 1994, however, had a specific-conductance value of about 15,000 $\mu\text{S}/\text{cm}$ and a dissolved-solids concentration that decreased by 7,600 mg/L to 10,200 mg/L. This well was abandoned in the late 1950s, presumably because of the increasing salinity. Although moderately saline water was apparently present in the Navajo aquifer when the well was drilled, increasingly higher concentrations of saline water moved into the wellbore during pumping of the well during 1952-55. Water from well N19 had a reported specific-conductance value of about 21,600 $\mu\text{S}/\text{cm}$ in 1966, when the well was drilled, but in 1989 the measured value was 10,600 $\mu\text{S}/\text{cm}$, a decrease of about 50 percent. Specific conductance of water from the well 1 year later (1990) however, had increased by 65 percent to 17,500 $\mu\text{S}/\text{cm}$.

Variations in dissolved-solids concentrations or specific-conductance values during relatively short periods cannot be readily explained by natural movement of water into or through the aquifer because hydraulic conductivity is too low to transmit water at rates comparable with the observed changes. Changes in concentration, however, appear to take place within one or a few years in wells that have been pumped and in artesian wells that have been opened to allow free flow, implying a localized pumping or wellbore effect. Large changes in salinity in wells N17 and N45 are not likely the result of drawdown-induced effects because these wells are pumped by windmills that operate intermittently and generally yield only several gallons per minute. If wells were open to formations that varied in salinity vertically in the vicinity of the well, however, pumping or other wellbore effects could potentially result in movement of water with different salinity into the wellbore, resulting in "apparent" increases or decreases in salinity with time. In addition, as discussed previously, in older wells that were not plugged and abandoned by current standards and procedures, or where the integrity of the cement and mud used to plug the wells has been compromised throughout time, saline water could potentially move uphole from the upper Paleozoic aquifer and into the Navajo aquifer. Where these wells are a short distance upgradient of

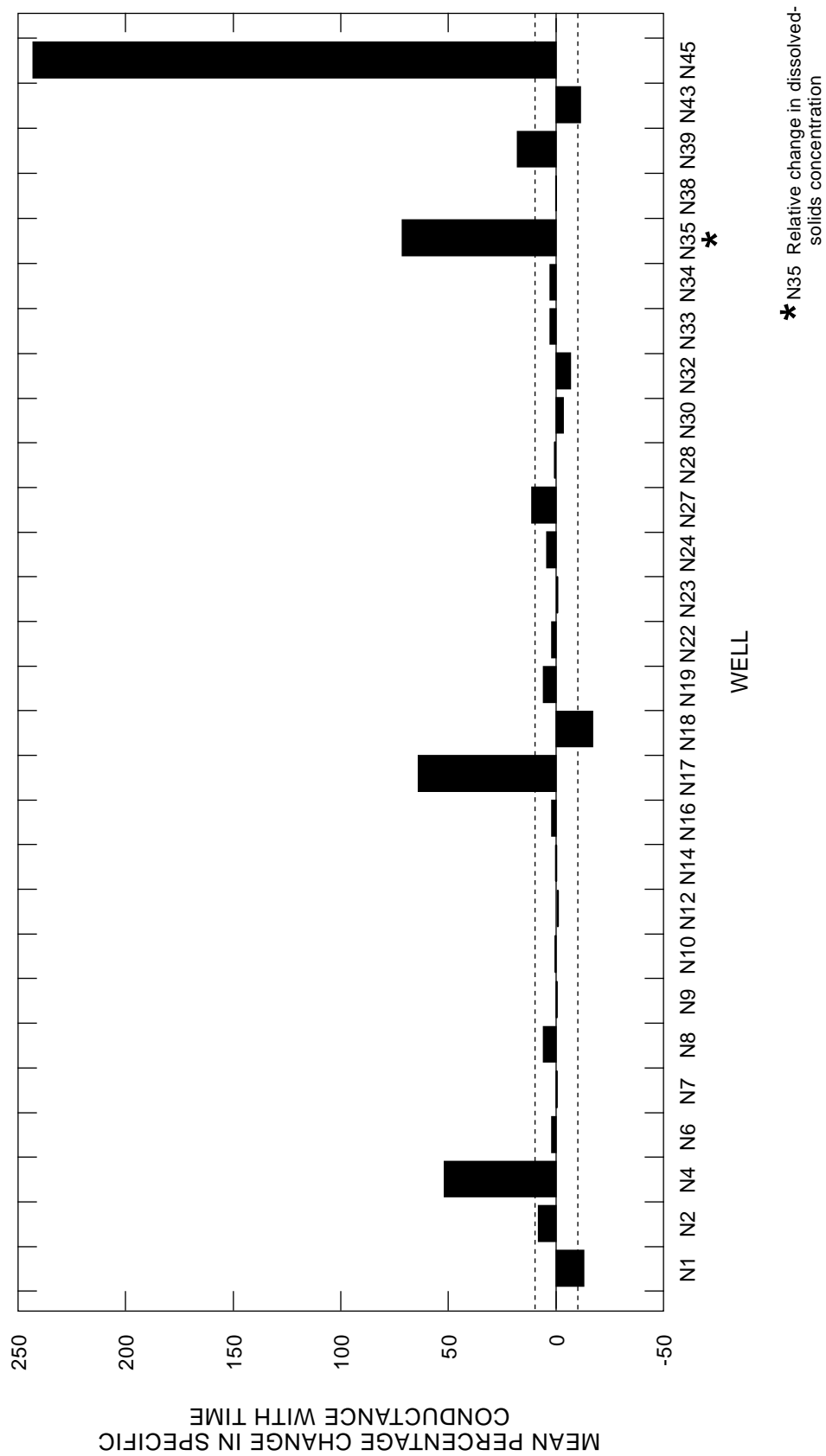


Figure 12. Variation in specific conductance of water from selected wells completed in the Navajo aquifer in and near the Greater Aneth Oil Field, San Juan County, Utah. Dashed lines represent plus or minus 10-percent variation.

water wells, saline water could potentially move into or be induced into wellbores and changes in salinity could take place within a historical time frame.

Water-quality monitoring during long periods of pumping, in conjunction with documenting differences in salinity with depth, could provide more definitive answers concerning changes in ground-water movement and water chemistry in the vicinity of wellbores. If observed variations in salinity are the result of pumping or localized wellbore effects, changes in salinity could be influenced by numerous factors, including well depth, well construction, duration of the pumping interval, duration of the non-pumping interval prior to pumping, depth of pump setting, perforated intervals, rate of discharge, and local geology.

Sources of Salinity to the Navajo Aquifer

Possible sources of salinity to the Navajo aquifer in the vicinity of the Greater Aneth Oil Field include (1) brine-disposal pits constructed during early stages of oil-field development; (2) downward migration of saline water from strata overlying the Navajo aquifer; (3) dissolution of evaporites in the Navajo aquifer by ground-water movement; (4) in situ water that has “stagnated” in the lower part of the Blanding Basin; (5) brine (produced water) injected into the Paradox Formation; and (6) saline water that is present in upper Paleozoic and lower Mesozoic formations. Each of these sources is evaluated in the following discussion.

Prior to injection of produced water back into the Paradox Formation beginning in the early 1960s, little is known about methods of disposal of produced water associated with oil. During early oil-field development in the late 1950s, disposal of produced water and other oil-field activities were not regulated by State or Navajo Nation agencies to the degree required by current (1994) standards (Gilbert Hunt, Utah Division of Oil, Gas, and Mining, oral commun., 1994). During the study, no information was obtained that would indicate the presence of disposal pits in the Greater Aneth Oil Field during oil-field development, and only two surface disposal pits were operated in the vicinity of the Greater Aneth Oil Field during the time of this study. A disposal pit between the communities of Bluff and Montezuma Creek in T. 40 S., R. 22 E., Sec. 14, has been operated since 1985, and a pit near Hatch Trading Post in T. 39 S., R. 24 E., Sec. 13, was operated from 1985 to 1989. Discussions with oil-field personnel during the study indicate that possible disposition of pro-

duced water included haulage of the water to disposal pits outside the area of the Greater Aneth Oil Field or reuse of the water for drilling operations. Records of produced water from the Aneth, Ratherford, and McElmo Creek Units prior to 1962 indicate that initially, daily water production was as low as 13 barrels per day and did not exceed 4,500 barrels per day, compared with as much as 100,000 barrels per day in the late 1970s (James Vanderhill, Mobil Exploration and Producing, U.S., Inc., written commun., 1995).

If a substantial volume of produced water were disposed of in surface pits, saline water zones characterized by high concentrations of sodium chloride would potentially exist in parts of the Morrison Formation or in other shallow aquifers in some areas. In areas where leakage of produced water from pipelines has taken place, saline water may be present in shallow aquifers. Generally, however, shallow aquifers in the vicinity of the oil field (alluvial, Dakota, and Morrison) yield relatively freshwater, and saline water in these aquifers is characterized by moderate concentrations of bicarbonate and sulfate rather than chloride (pl. 1). Consequently, surface disposal pits are not a likely source of salinity to the Navajo aquifer in this area.

Downward migration of saline water from strata overlying the Navajo Sandstone may be a potential source of salinity to the aquifer in some areas. Soluble minerals that are present in the Morrison and Carmel Formations, particularly gypsum, could be dissolved and moved downward into the upper parts of the Navajo aquifer where a downward hydraulic gradient exists. A downward hydraulic gradient between the Morrison and Navajo aquifers is present in areas where the Navajo aquifer is unconfined, near the recharge areas; however, downward movement of water would be inhibited by the Wanakah confining unit. In addition, an upward hydraulic gradient generally prevails where the Navajo aquifer is confined, in the vicinity of the Greater Aneth Oil Field. On the basis of water chemistry from aquifers in the overlying Morrison Formation, chloride concentrations are generally not high enough to provide a substantial source to, or account for the high concentrations of chloride in, the Navajo aquifer. The Carmel Formation in other parts of Utah contributes sulfate-rich water to the upper part of the Navajo Sandstone (Spangler and others, 1993, p. 40) and could be a potential source of salinity to some parts of the Navajo aquifer in the study area where sulfate-dominated water is present.

Saline water derived from localized dissolution of evaporites that were present in the Navajo aquifer

also has been proposed as a potential source of salinity (Buck Steingraber, Mobil Exploration and Producing, U.S., Inc., oral commun., 1993). Eolian deposits have been associated with both coastal and inland desert environments throughout geologic time and consist of extensive areas of dune sand, sand sheets, interdunes, and evaporative pans or sabkhas (Ahlbrandt and Fryberger, 1982, p. 11). Relative percentages of these lithologies may vary from one eolian system to another and from coastal to inland environments. Along coastal areas, interdunal areas and sabkhas may be subject to periodic inflows of marine water that concentrate evaporites, particularly halite (Fryberger and others, 1983, p. 288). Ground water in these areas also may be drawn up into interdunal areas by water-table fluctuations or by capillary processes by which saline water can evaporate and precipitate evaporites. Where eolian systems are present in inland desert environments, such as that exemplified by the Navajo Sandstone, evaporites also may be precipitated in interdunal areas. This process may take place where shallow water tables fluctuate beneath the lower, interdunal areas or where wind deflation has excavated down to the water table (Handford, 1981, p. 1685). Evaporation takes place by capillary concentration along the air-saturated sand interface and may result in the precipitation of evaporite (gypsum and halite) cements and crusts.

Interdunal deposits in the Navajo Sandstone consist primarily of lenticular beds of very fine crystalline, cherty limestone and dolomite and thinly-bedded siltstones and shales (McKee, 1979, p. 214; Harshbarger and others, 1957, p. 19; and Peterson and Phipps, 1979, p. B4). The Namib Sand Sea in southwestern Africa appears to be the closest modern analogue to the depositional environment of the Navajo Sandstone (Lancaster and Teller, 1988, p. 91). No direct evidence of evaporites appears to have been preserved in interdunal lithologies of the Navajo Sandstone (Fred Peterson, U.S. Geological Survey and Helmut Doelling, Utah Geological Survey, oral commun., 1995), or the correlative Nugget Sandstone where it is deeply buried in the Overthrust Belt of northeastern Utah (Sandra Lindquist, Amoco Production Company, oral commun., 1995). In studies of the Entrada Sandstone, Kocurek (1981) states that "no direct evidence for evaporites was seen in Entrada interdune deposits"; however, indirect evidence of exposure to air and former evaporite deposition in both of these eolian units is present as polygonal fractures, silicified nodules, brecciated laminae, and wavy, irregular bedding (Kocurek and Hunter, 1986; Schenk and

Peterson, 1991, p. 1139; and Kocurek, 1981). Erosional and depositional features that also indicate exposure to air have been preserved along regional unconformities in the Navajo Sandstone (Kocurek and Hunter, 1986). In studies of the Nugget Sandstone in northeastern Utah, Schenk and Peterson (1991, p. 1139) interpreted the wavy, irregular bedding in interdunal areas to be the result of displacive growth of salt crystals or crumbling of thin, algal mats. Analysis of silicified nodules within carbonate lenses have shown a fibrous, porous structure containing remnant anhydrite crystals, elongate pores, and other textures that suggest replacement of former anhydrite nodules by silica (Kocurek and Hunter, 1986). Although the depositional environment of the Navajo Sandstone was conducive to the development of evaporitic interdunal lithologies, these were limited in areal and vertical extent. Doe and Dott (1980, p. 800-803) estimated that only about 10 percent of the Navajo sand sea was deposited in a wet, interdunal environment.

Evaporites that may have been deposited and preserved in interdunal deposits in the Navajo Sandstone potentially could have been dissolved by fresh meteoric water moving downgradient toward discharge areas along the San Juan River, resulting in salinization of the Navajo aquifer. Because interdunal areas and hence, evaporite deposition were localized, substantial differences in concentrations of dissolved solids might be expected in water from wells that are relatively close to one another, as documented during this study. Exposure of the Navajo Sandstone to recharge, and groundwater movement through the Navajo aquifer since the Tertiary Period when uplift of strata in the recharge areas was initiated, likely would have removed more soluble minerals, particularly halite, and "modern" water would be expected to be less saline than that observed (Kimball, 1992, p. 98). Kocurek and Hunter (1986) also have suggested that removal and siliceous replacement of former evaporites that might have been present in the Navajo Sandstone took place during early diagenesis and prior to compaction of the sandstone, implying that evaporites were not present in the Navajo aquifer after the ground-water flow system was initiated.

Barnes (unpub. data, 1959, p. 12) postulated that the negative structural closure of the Blanding Basin in the discharge area of the San Juan River inhibited upward movement of ground water and resulted in stagnation of water in the deeper parts of the basin. According to Barnes, this restriction of ground-water circulation resulted in "mineralization of ground water

in the DeChelly Sandstone and salinity in the Navajo aquifer.” Although ground-water movement from recharge areas to the San Juan River is probably down-dip in the basin, discharge is controlled by hydraulic-head gradients, horizontal hydraulic conductivity of the sandstone aquifers, and vertical hydraulic conductivity of the confining units where water moves upward to the river. Less permeable lithologies in the Navajo aquifer, such as those associated with interdunes, could locally impede ground-water movement; however, in dune-interdune systems, such as those of the Nugget and Navajo Sandstones, interdunal deposits are generally not permeability barriers between the more permeable, adjacent dunes (Lupe and Ahlbrandt, 1979, p. 251). Although discharge of water to the San Juan River is likely inhibited by confining units in the Morrison Formation through which water from the Navajo aquifer must rise, the regional effects of this impeded flow are difficult to assess.

Brines associated with produced oil in the Paradox Formation also have been suggested as the source of salinity to the Navajo aquifer in a part of this area (Kimball, 1992, p. 89). Because brine is injected back into the producing oil formations through wells, avenues for upward movement of the injected water into the Navajo aquifer were presumed to be the annulus between the casing of the injection well and the borehole wall or upward through the boreholes of plugged and abandoned oil wells that also penetrate the Paradox Formation. Locations of wells containing water with dissolved-solids concentrations that are higher than those of freshwater only in the vicinity of the Greater Aneth and satellite oil fields also suggest a relation between salinity in the Navajo aquifer and oil-field location (pl. 1). In addition, if hydraulic head in the Paradox Formation was higher than that in the Navajo aquifer, saline water theoretically could have moved upward through the avenues mentioned above and into the Navajo aquifer. Results of geochemical analysis using multivariate statistics and pattern-recognition modeling during this study have indicated, however, that oil-field brine injected back into the Paradox Formation is not the likely source of salinity to the Navajo aquifer. Results of these investigations are discussed in greater detail in the following sections of this report.

The presence of saline water in upper Paleozoic strata, particularly the Cutler Formation, commonly has been reported by drillers in the Greater Aneth Oil Field (Utah Division of Water Rights, Report of Water Encountered During Drilling, unpub. data). Results of analysis of water samples collected during this study

from four water source wells in the upper Paleozoic Cutler Formation and lower Mesozoic Chinle Formation (Shinarump Member) and from a water sample collected during a drill-stem test of the DeChelly Sandstone in 1960 substantiate that saline water is present in these formations at a depth ranging from 2,500 to 3,300 ft in the vicinity of the Greater Aneth Oil Field. Assuming a potential exists for upward movement of saline water from upper Paleozoic strata through the Chinle Formation and into the Navajo aquifer, saline water also might be expected to be present throughout most of the stratigraphic section above the Shinarump Member. Very little chemical or hydraulic-head data exists for this massive part of the formation, however, and this could not be evaluated. Results of geochemical analysis obtained using multivariate statistics and pattern-recognition modeling have shown a correlation between water in upper Paleozoic and lower Mesozoic aquifers and water in the Navajo aquifer, implying a potential source of salinity to the Navajo aquifer. Results of these investigations are discussed in the following sections of this report.

Geochemical Characterization of Salinity in the Navajo Aquifer

Bromide- and iodide-to-chloride weight ratios were used to determine different conservative chemical signatures of the oil-field brine (OFB), non-OFB, the upper Paleozoic aquifer, and comingled (mix of OFB and water from alluvial aquifer) end-member waters. These constituents have been used successfully in previous ground-water salinity studies to differentiate OFB from non-OFB (Whittemore, 1988; and Richter and Kreitler, 1991). Neither constituent generally participates in chemical reactions in non-brine systems (Whittemore, 1988). $\delta^{18}\text{O}$, δD , and $\delta^{87}\text{Sr}$ values also are used to determine sources of water to ground-water systems and were used to determine whether OFB or water from the upper Paleozoic aquifer is a possible source of salinity to the Navajo aquifer.

Bromide-to-Chloride Ratios

Bromide concentration is enriched in organic materials (Whittemore, 1988; and Maida, 1989), possibly providing considerable differences in the relative amount of bromide in samples of OFB (enriched with organic materials) and other probable saline sources such as non-OFB (limited in organic materials) and

upper Paleozoic aquifer water. Bromide and chloride concentrations in water samples collected from the Navajo aquifer, San Juan River, adjacent alluvial aquifer, the upper Paleozoic aquifer, and the Paradox Formation (OFB, non-OFB, and comingled water) were compared with the bromide-to-chloride ratio of modern ocean water of 0.00344 (fig. 13). In general, water samples from the San Juan River and from a well completed in the shallow alluvium along the San Juan River plot close to the ratio of modern ocean water, suggesting an atmospheric bromide source. Water samples from the Navajo aquifer with a chloride concentration less than or equal to 60 mg/L, in general, also plot close to the ratio of modern ocean water (median = 0.0035, $n = 10$); however, as chloride concentration increases, most of the water samples plot below the modern ocean water ratio with a median bromide-to-chloride ratio of 0.0011 ($n = 36$). Non-OFB and upper Paleozoic aquifer samples become depleted in bromide relative to modern ocean water, possibly indicating a limited amount of organic matter and relatively low bromide concentrations in chloride minerals. According to Whittemore (1988), halite formed during the latter stages of ocean-water evaporation has a bromide-to-chloride ratio of 0.001, substantially less than the modern ocean-water value of 0.00344. In contrast, samples of OFB and comingled water are generally enriched in bromide relative to modern ocean water. The median bromide-to-chloride ratio for the five OFB samples is 0.0056, indicating the influence of organic material on the OFB. Total organic carbon concentrations in the five OFB samples ranged from 5.2 to 180 mg/L (table 8).

The bromide-to-chloride weight ratios of five potential groups of end-member waters were plotted with chloride concentrations (fig. 14). The five groups of end-member waters are defined as follows: (1) water from upgradient areas of the Navajo aquifer, defined by a chloride concentration less than or equal to 60 mg/L; (2) water from the upper Paleozoic aquifer; (3) OFB from the Paradox Formation in the study area; (4) non-OFB from the Paradox Formation northeast of the study area; and (5) comingled water composed of a mixture of alluvial aquifer water and OFB. The ratio of alluvial aquifer water to OFB in the comingled water is variable; however, during the time of sample collection the proportion of alluvial aquifer water was 8 percent at site PRD1 and 33 percent at site PRD4. To work with values greater than 1, the bromide-to-chloride weight ratios are multiplied by 10,000.

Significant differences between the brine end-member waters are shown in figure 14. The three non-

OFB samples from the Paradox Formation have small bromide-to-chloride weight ratios that are less than 10. In contrast, the five OFB and two comingled water samples from the study area have bromide-to-chloride weight ratios much greater than 10. Bromide-to-chloride weight ratios that exceed 10 are typical of other OFBs in the United States and probably reflect decomposition of bromide-enriched organic matter associated with oil reservoirs (Whittemore, 1988). The bromide-to-chloride ratios of the four end-member water samples from the upper Paleozoic aquifer plot about halfway between the OFB and comingled samples and the non-OFB samples (fig. 14).

Salinization of water from the Navajo aquifer with different end-member water composition should be reflected in the direction of change in the bromide-to-chloride weight ratio as chloride concentration increases. Salinization of water with a low chloride concentration (less than or equal to 60 mg/L) from the Navajo aquifer with OFB would produce a water with equal or larger bromide-to-chloride weight ratios (fig. 14). In contrast, salinization of water from the Navajo aquifer with either non-OFB or water from the upper Paleozoic aquifer would produce a water with smaller bromide-to-chloride weight ratios (fig. 14).

A series of mixing models was constructed using the different bromide-to-chloride weight ratios of the previously defined end-member waters to determine which saline end-member may be contributing to the salinity of water in the Navajo aquifer (fig. 15). For the purposes of the mixing models, end-member chloride and bromide concentrations were defined as the mean concentrations. Mixing lines between the four potential saline end-member waters with the end-member water from the Navajo aquifer (chloride concentration less than or equal to 60 mg/L) were constructed using the equation

$$C_{mix} = C1*V + C2*(1-V) \quad (3)$$

where:

C_{mix} is the bromide or chloride concentration of the end-member mixture,

$C1$ and $C2$ are the bromide or chloride concentrations of the end-member water, and

V is the volume fraction of the Navajo aquifer end-member water.

Thirty-six water samples from the Navajo aquifer with chloride concentrations greater than 60 mg/L were compared with the ratio shown on the constructed mixing lines (fig. 15). In water from the Navajo aquifer, the bromide-to-chloride weight ratio decreases with

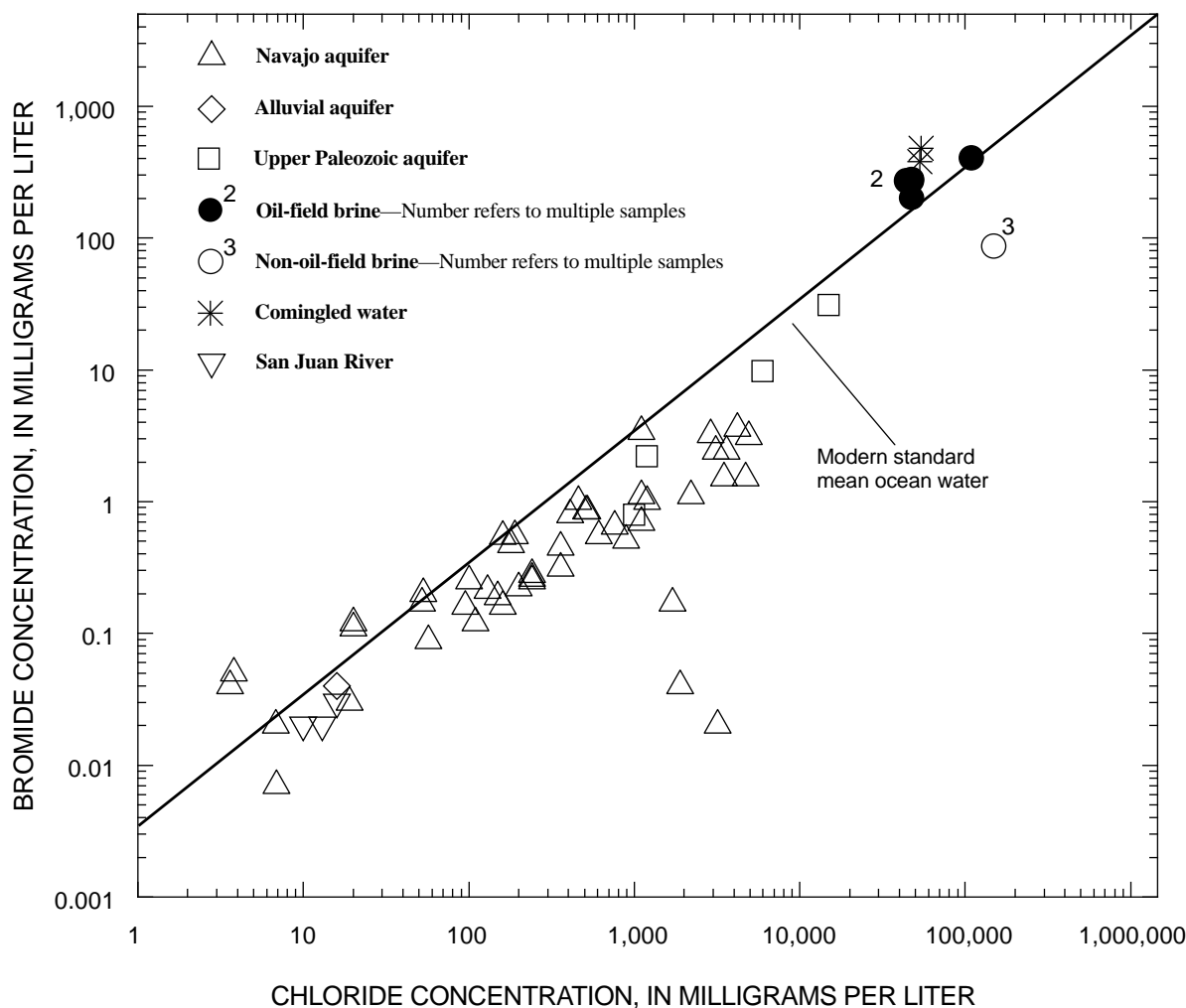
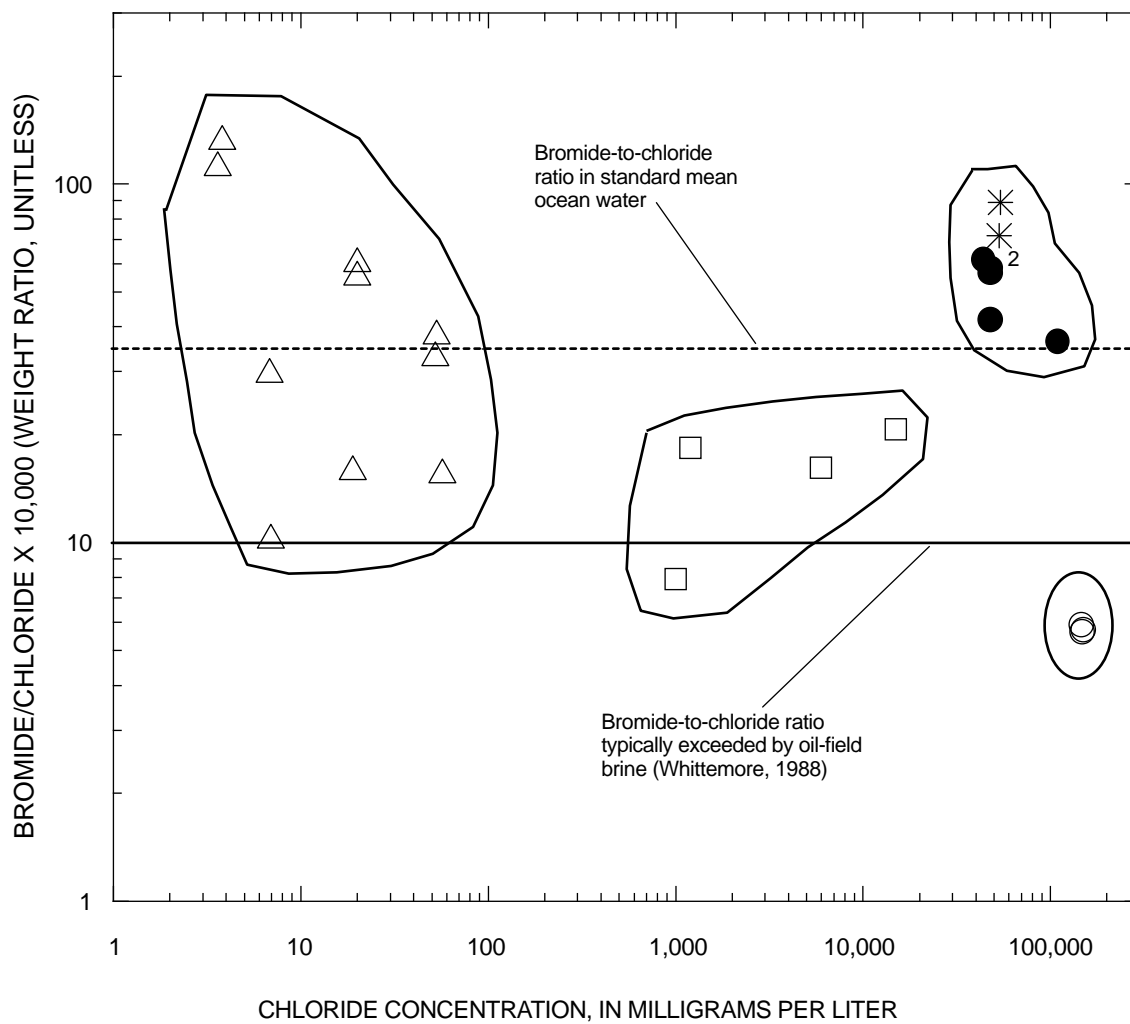


Figure 13. Bromide and chloride concentration in water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, compared with the bromide-to-chloride weight ratio of modern standard mean ocean water.

increasing chloride concentration, generally following the end-member mixing lines constructed with the mean non-OFB and the upper Paleozoic aquifer end-member water composition (fig. 15). If the salinity source was OFB or comingled injection water, bromide-to-chloride ratios in water from the Navajo aquifer should follow the upper mixing lines as chloride concentration increases (fig. 15). This is not the trend shown and indicates that neither OFB nor comingled injection water is the source of salinity.

Because of the large difference in bromide concentrations between the upgradient Navajo aquifer water and the comingled injection water, only a small volume of comingled injection water is required to produce a large increase in the bromide-to-chloride weight

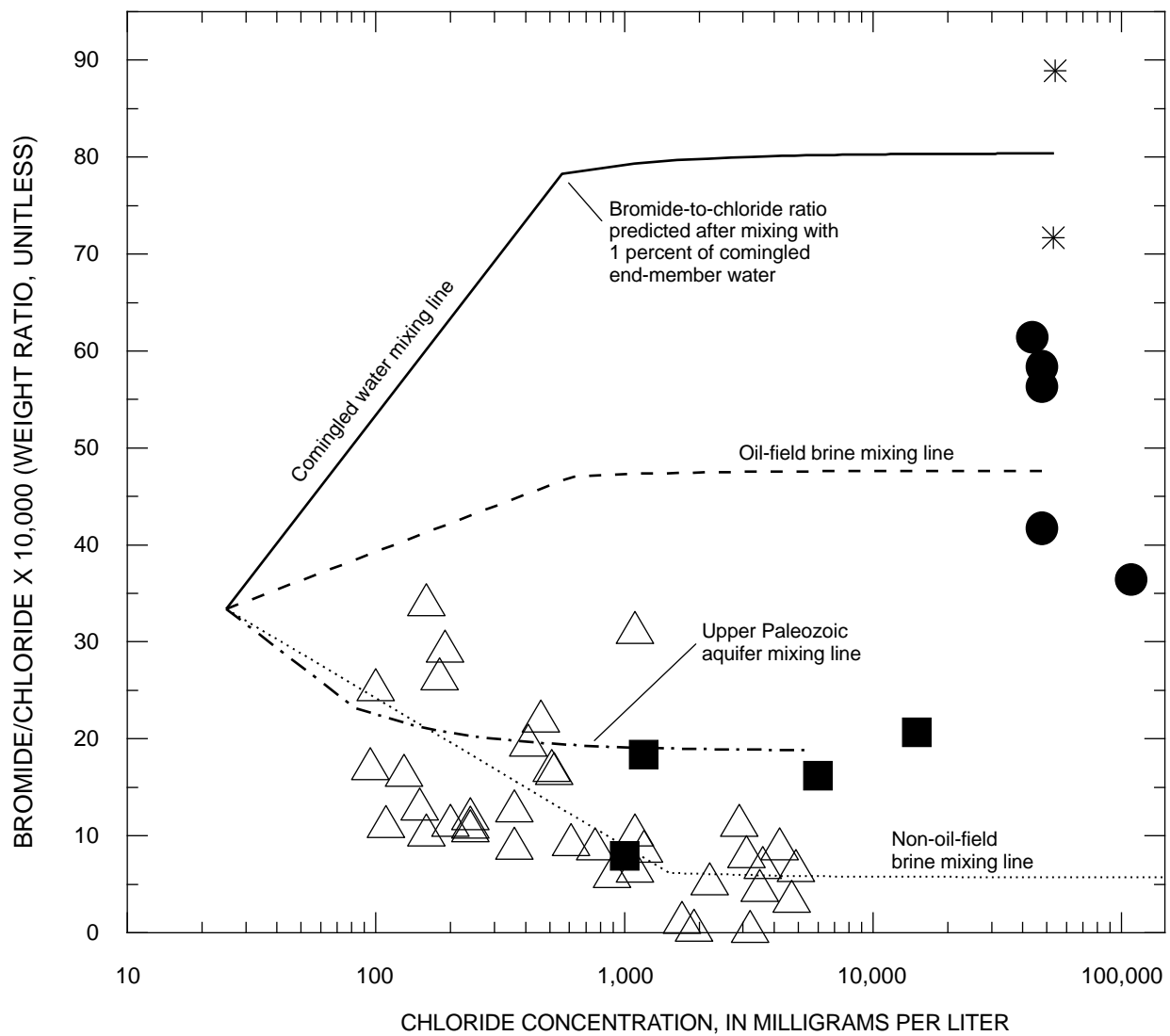
ratio. For example, a mixture of 1 percent comingled injection water with 99 percent Navajo aquifer end-member water would increase the bromide-to-chloride weight ratio from less than 40 to 78 in the resulting mixture (fig. 15). The sensitivity of the bromide-to-chloride ratio in Navajo aquifer water to small volumes of comingled injection water provides additional evidence that even small volumes of comingled injection water probably are not responsible for the salinity increases in the Navajo aquifer. Furthermore, the sensitivity of the bromide-to-chloride ratio in Navajo aquifer water to OFB and comingled injection water provides a useful tool for future monitoring of potential OFB contamination in the study area.



EXPLANATION

- △ Navajo aquifer—Chloride concentration less than or equal to 60 milligrams per liter
- Upper Paleozoic aquifer
- ² Oil-field brine—Number refers to multiple samples
- Non-oil-field brine
- * Comingled water

Figure 14. Bromide-to-chloride weight ratios compared with chloride concentration in end-member water groups in and near the Greater Aneth Oil Field, San Juan County, Utah.



EXPLANATION

- △ Navajo aquifer
- Upper Paleozoic aquifer
- Oil-field brine
- ✱ Comingled water

Figure 15. Mixing lines constructed between potential saline end-member water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, compared with bromide-to-chloride weight ratios in water from the Navajo aquifer with chloride concentrations greater than 60 milligrams per liter.

Iodide-to-Chloride Ratios

Similar to bromide, iodide concentration can be enriched in organic material and can provide a useful geochemical tool to differentiate salinity sources (Richter and Kreitler, 1991). Iodide is also relatively conservative in ground-water systems; however, it can be affected by sorption with iron and aluminum (Maida, 1989). A plot of the iodide-to-chloride weight ratios compared with increasing chloride concentrations also indicates that OFB and comingled injection water are not the source of salinity to the Navajo aquifer (fig. 16). The five OFB and two comingled injection water samples have enriched iodide-to-chloride weight ratios that are substantially larger than the ratios reported for halite solution brines (Richter and Kreitler, 1991). Iodide-to-chloride weight ratios in water samples from the Navajo aquifer trend toward smaller ratios characteristic of non-OFB (halite solution brine) and the upper Paleozoic aquifer ratios (fig. 16). The best-fit line through the Navajo aquifer samples trends toward the composition of halite solution brines and is far removed from the composition of OFB in the study area (fig. 16). Out of the three saline source water types plotted in figure 16, water samples from the upper Paleozoic aquifer appear to be the most reasonable end-member water.

A series of mixing models similar to those constructed with the bromide-to-chloride data were constructed using the different iodide-to-chloride weight ratios of the previously defined end-member waters to determine which saline end-member may be contributing to the salinity of water in the Navajo aquifer. Because of the lack of iodide analyses for non-OFB, a non-OFB end-member mixing model could not be constructed; however, end-member mixing models were constructed using the three remaining end-member water types (OFB, comingled injection water, and water from the upper Paleozoic aquifer) (fig. 17).

Mixing lines between the three saline end-member waters and the end-member water from the Navajo aquifer (chloride concentration less than or equal to 60 mg/L) were constructed using the equation

$$C_{mix} = CI * V + C2 * (1 - V) \quad (4)$$

where:

C_{mix} is the iodide or chloride concentration of the end-member mixture,

CI and $C2$ are the iodide or chloride concentrations of the end-member water, and

V is the volume fraction of the Navajo aquifer end-member water.

Thirty-six water samples from the Navajo aquifer with chloride concentrations greater than 60 mg/L were compared with the ratio shown on the constructed mixing lines (fig. 17). In water from the Navajo aquifer, the iodide-to-chloride weight ratio decreases with increasing chloride concentration, generally following the end-member mixing lines constructed with the mean upper Paleozoic aquifer end-member water composition. If the salinity source was OFB or comingled injection water, iodide-to-chloride ratios in water from the Navajo aquifer should follow the upper mixing lines as chloride concentration increases (fig. 17). This is not the trend shown and is in agreement with the results of the bromide-to-chloride data and mixing model, which indicate that neither OFB nor comingled injection water is the source of salinity.

Oxygen and Hydrogen Isotopes

Although the bromide-to-chloride and iodide-to-chloride weight ratios provide strong evidence for discounting the role of OFB as even a minor source of salinity to water in the Navajo aquifer, additional geochemical evidence is needed to confirm these initial results. The stable isotopes of oxygen and hydrogen in water provide a useful geochemical tool to determine water sources (Drever, 1988). The stable isotopes of oxygen (^{18}O and ^{16}O) and hydrogen (^2H and ^1H) have been used in numerous OFB studies to differentiate salinity sources (Richter and Kreitler, 1991). The substantial isotopic enrichment in OFB and injection water samples relative to water samples from the Navajo aquifer (fig. 18) is well suited to determine if the OFB and injection water are possible salinity sources.

The isotopic composition of ground- and surface-water samples in the study area was compared with the North American (Craig, 1961) and arid-zone (Welch and Preissler, 1986) meteoric water lines (fig. 18). Most of the water samples from the Navajo aquifer with a $\delta^{18}\text{O}$ value less than about -13 permil plot close to the North American meteoric water line. The isotopically light signature of these waters, which plot above the arid-zone meteoric water line, reflects the major contribution to recharge from snowmelt in the high-altitude mountain ranges, particularly to the north of the study area. Two composite snow samples collected from the Abajo Mountains plot along the North American meteoric water line and are isotopically light relative to water from the Navajo aquifer. Median isotopic values of water samples from the San Juan River and adjacent alluvium have similar isotopic values and plot close to

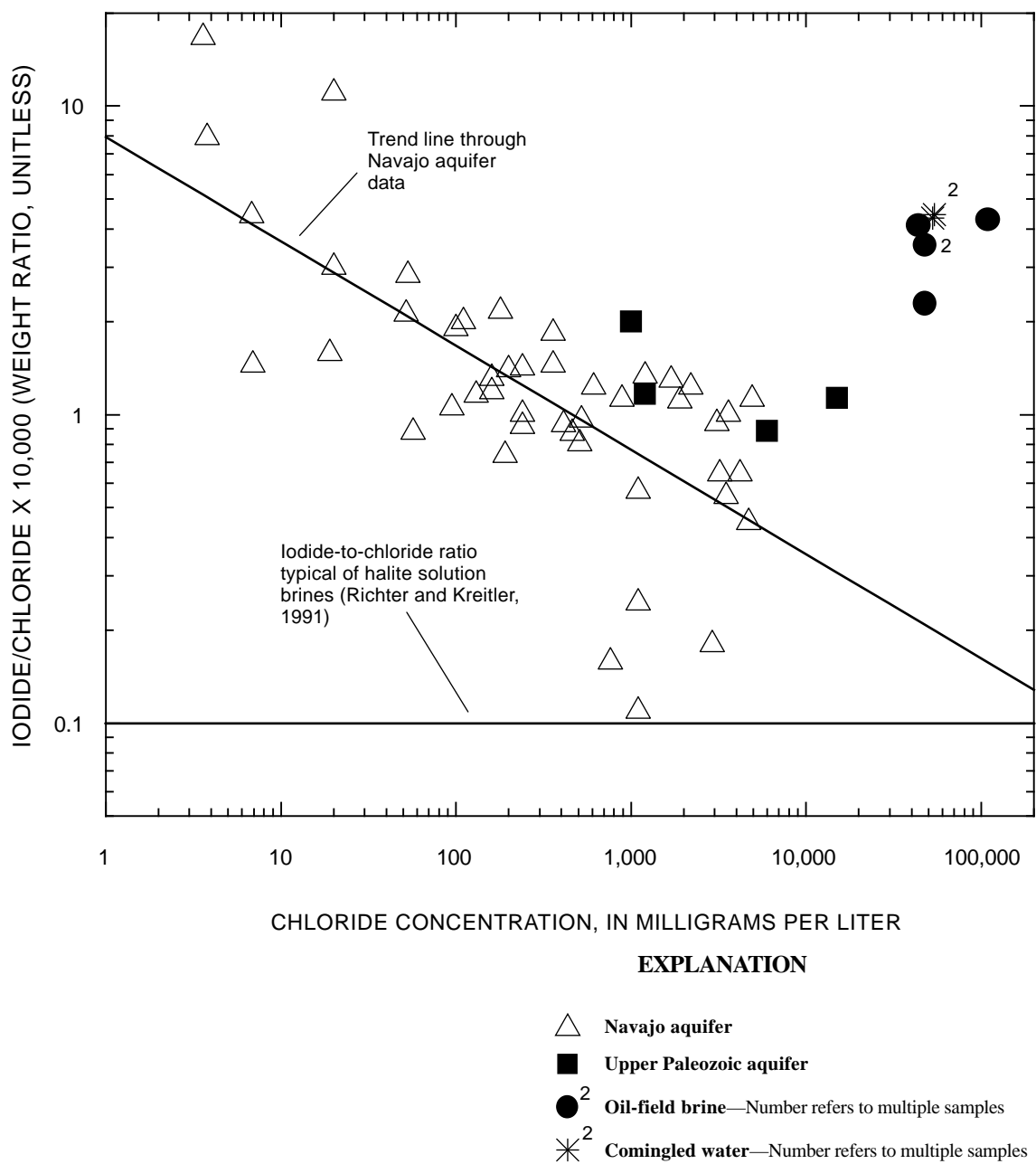


Figure 16. Iodide-to-chloride weight ratios compared with chloride concentration in water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah.

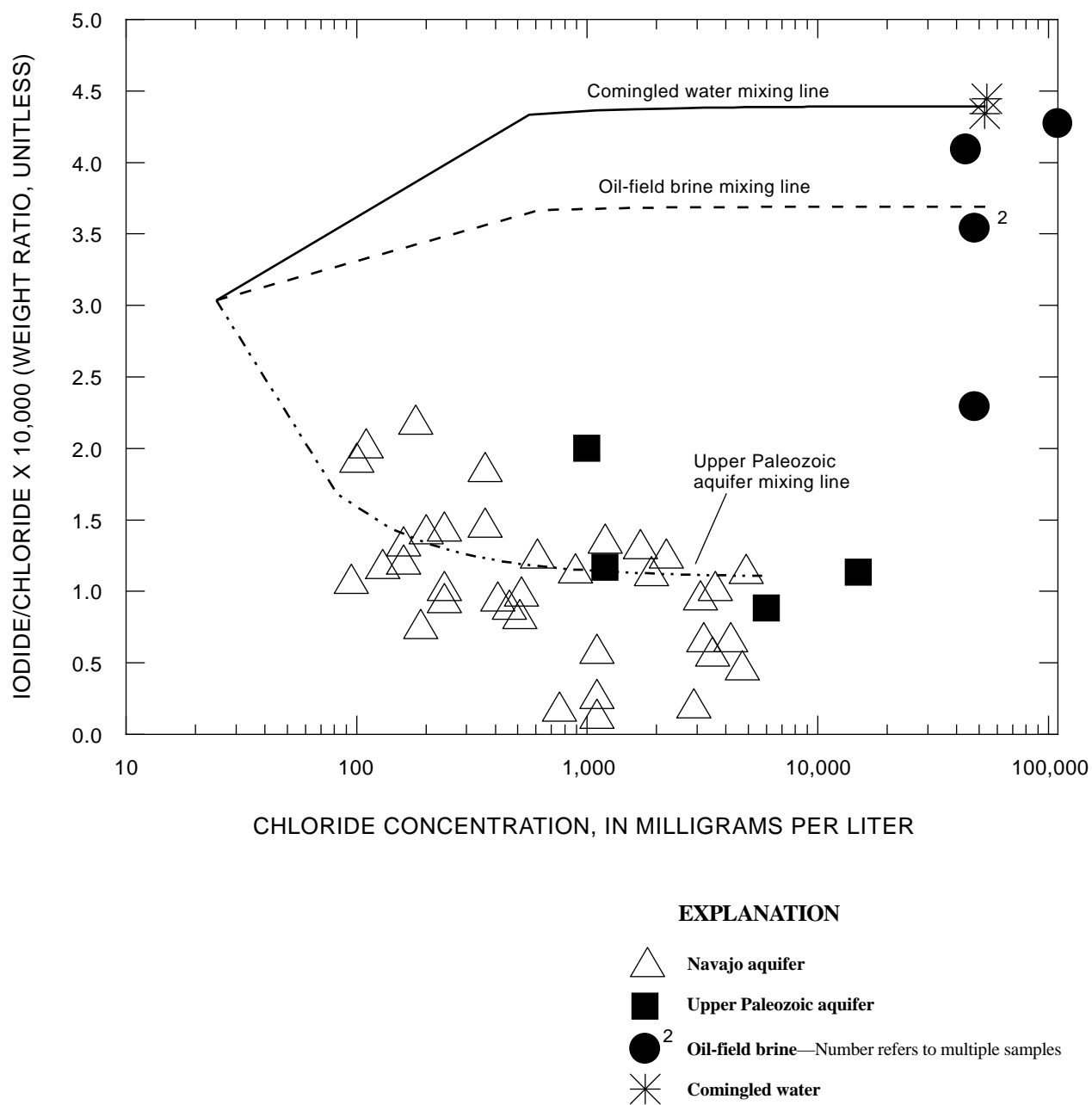


Figure 17. Mixing lines constructed between potential saline end-member water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, compared with iodide-to-chloride weight ratios in water from the Navajo aquifer with chloride concentrations greater than 60 milligrams per liter.

the North American meteoric water line (fig. 18). The OFB and injection water samples from the study area are isotopically enriched in ^{18}O and D relative to other samples and plot considerably below both meteoric water lines. These ratios are typical of residual water from Paradox Formation evaporites that formed in a closed basin.

As water from the Navajo aquifer becomes isotopically enriched in ^{18}O and D, the samples consistently fall below the North American meteoric water line and plot more in line with the arid-zone meteoric water line (fig. 18). The deviation of Navajo aquifer samples from the North American meteoric water line may be caused by (1) mixing of meteoric recharge water with isotopically enriched (with ^{18}O and D) water from a closed basin, or (2) geographic segregation of water in the Navajo aquifer determined by different isotopic signatures of recharge water. Both scenarios will be addressed separately in the following paragraphs.

A mixing line was constructed to best fit the trend shown by the isotopically enriched (with ^{18}O and D) water samples from the Navajo aquifer (fig. 19A). The constructed mixing line does not indicate mixing with the most isotopically enriched (with ^{18}O and D) Ismay brine sample or the isotopically lighter OFB and injection water samples from Aneth, Ratherford, White Mesa Unit, and McElmo Creek injection sites.

A mixing line constructed between the isotopic composition of the Ismay OFB and water from the San Juan River alluvial aquifer explains the shift from enriched isotopic values of OFB from the Ismay injection facility to lighter isotopic values of OFB at the Aneth, Ratherford, White Mesa Unit, and McElmo Creek injection facilities (fig. 19B). Recovered brine volumes at the Ismay injection facility are sufficient; therefore, make-up water from the alluvial aquifer is not needed for injection operations. In contrast, varying amounts of isotopically lighter make-up water from the alluvial aquifer have been used in the past, as well as currently (1994), for injection operations at the Aneth, Ratherford, White Mesa Unit, and McElmo Creek injection facilities. The mixing and continued recycling of the injection water at these four facilities has caused a distinctly lighter isotopic composition in these OFB and injection water samples.

A mixing line was constructed between the injection water samples and freshwater from the Navajo aquifer (fig. 19C) to determine if the isotopic enrichment and deviation from the North American meteoric water line observed for selected water samples from the Navajo aquifer may be the result of mixing with the

OFB or injection water. The mixing line shown in figure 19C was used to estimate the proportion of isotopically enriched (with ^{18}O and D) injection water that theoretically may have mixed with isotopically light water from the Navajo aquifer to produce the isotopically enriched water in selected samples from the Navajo aquifer. For illustration purposes, water samples from wells N45 and N18 were used as examples of water from the Navajo aquifer affected by isotopic enrichment, and water from well N6 was used to represent isotopically light water from the Navajo aquifer (fig. 19C). On the basis of only the isotopic mixing model, sample N45 appears to be a mixture of 71 percent N6 water and 29 percent injection water; and sample N18 appears to be a mixture of 28 percent N6 water and 72 percent injection water (table 9).

The validity of the mixing proportions of freshwater (well N6) and injection water, which were estimated by the isotopic mixing model for wells N45 and N18, was tested using chloride mass balance (table 9). The chloride concentrations predicted by the isotopic mixing model for wells N45 and N18 are 43 and 8 times larger than the measured chloride concentrations in isotopically enriched (with ^{18}O and D) water samples from the Navajo aquifer. Naftz and Spangler (1994, p. 1132) used a simulated isotopic composition of injection water and determined that isotopic enrichment in water samples from the Navajo aquifer could not be the result of mixing with OFB or injection water. On the basis of these results and consistent with the bromide and iodide results presented previously, OFB and injection water are not the source of salinity to the Navajo aquifer.

An alternative to OFB and injection water that may cause the isotopic enrichment of selected water samples from the Navajo aquifer is the influence of lower-altitude recharge signatures more characteristic of isotopically enriched (with ^{18}O and D) arid-zone precipitation. In general, water samples from wells completed in the Navajo aquifer in area 1 have distinctly lighter (more negative or smaller) $\delta^{18}\text{O}$ and δD values relative to water samples from wells in area 2 (fig. 20). Furthermore, isotopic values of water samples from wells in area 2 are more aligned with the arid-zone meteoric water line (fig. 20).

The presence of lower-altitude recharge areas in area 2 could cause the larger isotopic values of water samples from the Navajo aquifer relative to isotopic values of water samples from wells in area 1 (Rozanski and others, 1993, p. 5). For example, water from well N43 in the upgradient part of area 2 has a $\delta^{18}\text{O}$ value of

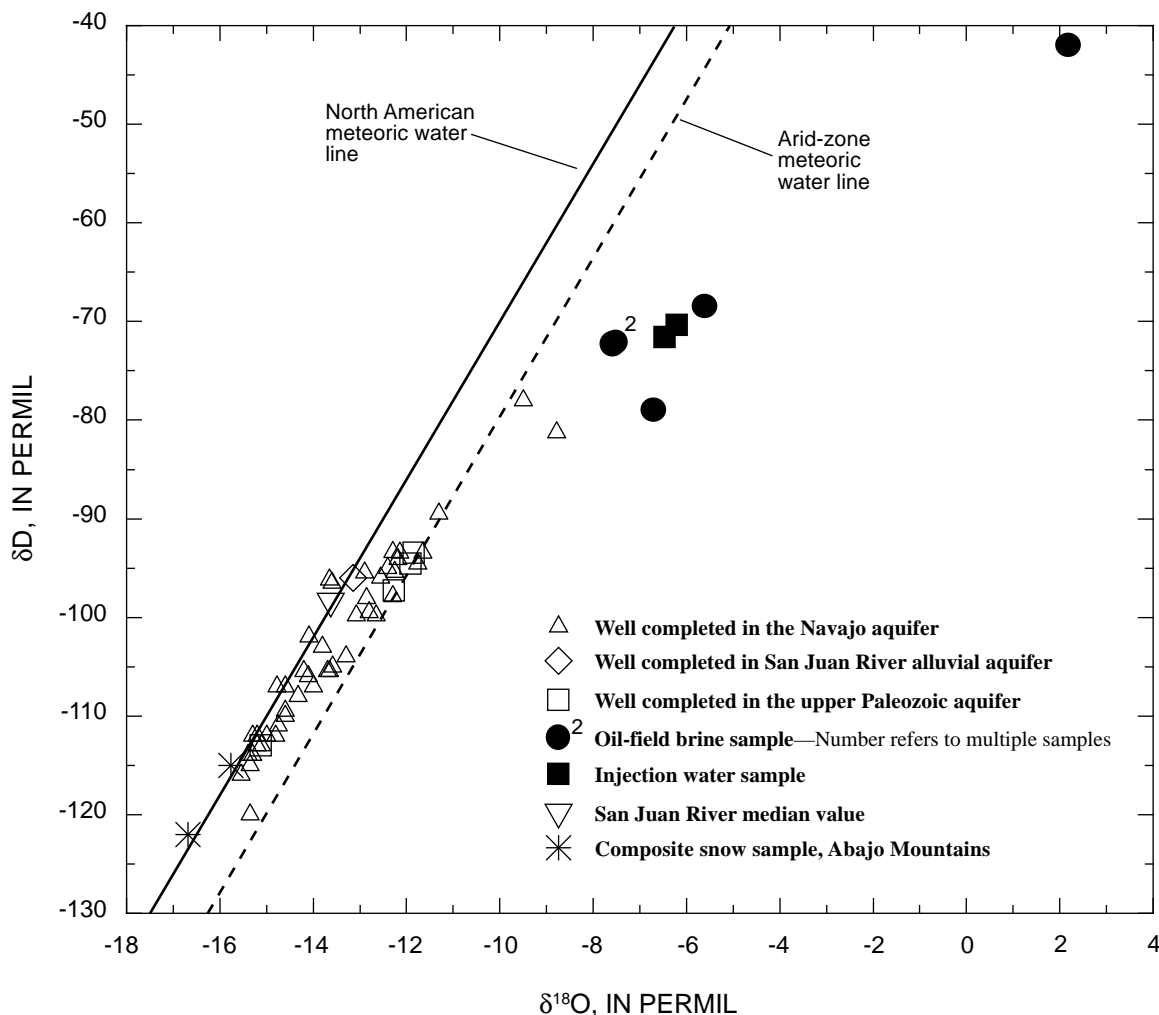


Figure 18. The δD and $\delta^{18}O$ values of ground-water, surface-water, and snow samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah, in relation to the North American and arid-zone meteoric water lines.

-9.5 permil, which is larger than values in water samples from downgradient wells in area 1. The low chloride concentration in water from well N43 (3.8 mg/L) further supports that this sample represents recharge water.

Although actual precipitation samples were not collected from recharge areas to area 2, water samples from an alluvial aquifer and an ephemeral stream draining lower altitudes in the study area have similar isotopic values as water samples from wells in area 2 (fig. 20). A water sample from a spring discharging from the Bluff Sandstone (chloride concentration of 17 mg/L), representative of a local flow system, also has enriched (with ^{18}O and D) isotopic values that plot along the

arid-zone meteoric water line, similar to values of water samples from the Navajo aquifer in area 2 (fig. 20). The $\delta^{18}O$ and δD values from two precipitation samples collected in the Abajo Mountains (recharge to area 1) are similar to isotopic values of water samples from the Navajo aquifer in area 1 (fig. 20).

Water from three of the four wells completed in the upper Paleozoic aquifer contains similar $\delta^{18}O$ and δD values relative to values of water from wells completed in the Navajo aquifer in area 2 (fig. 20). In contrast, water from three of the four wells completed in the upper Paleozoic aquifer contains distinctly heavier (more positive or larger) isotopic values relative to val-

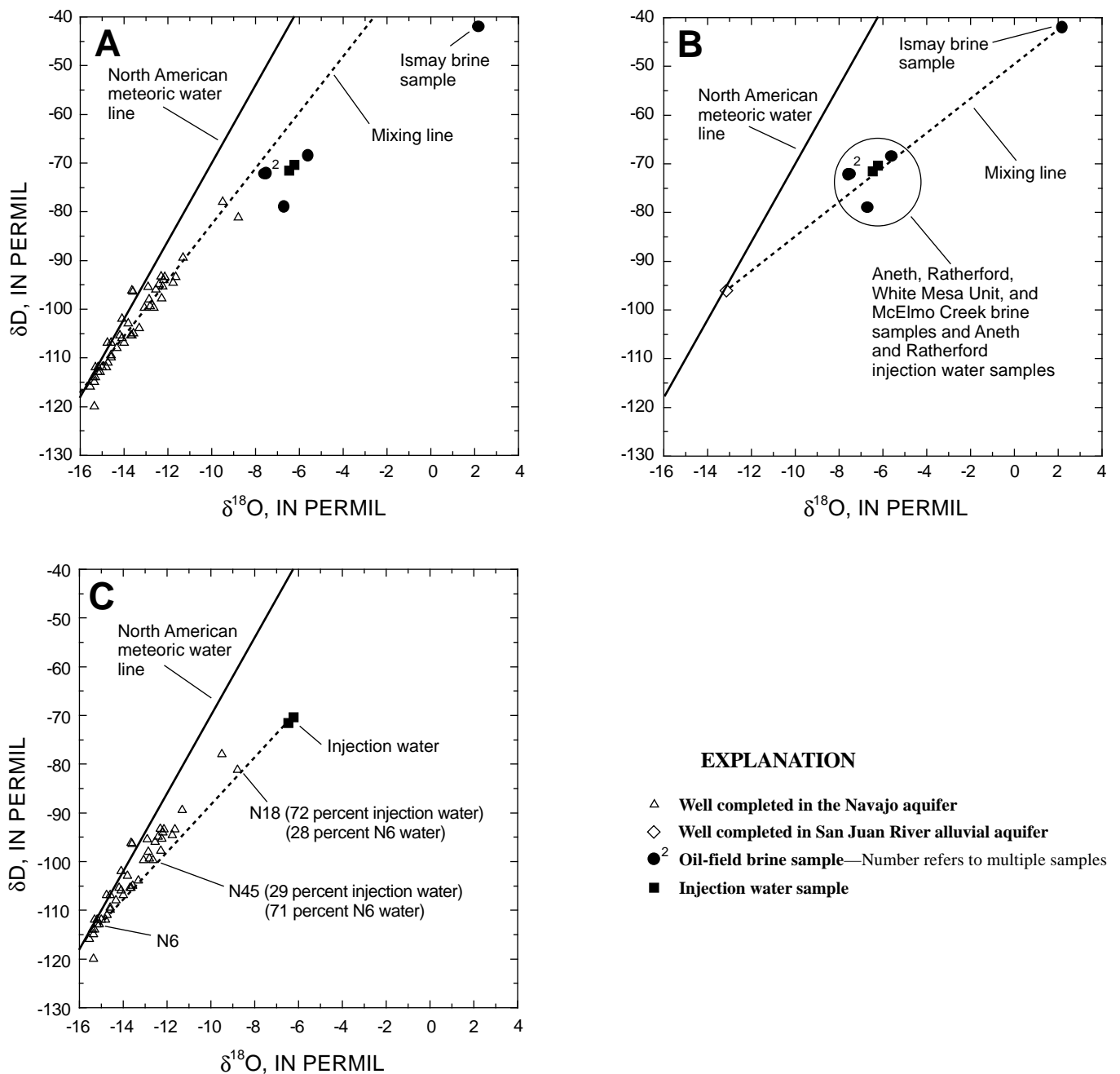


Figure 19. Mixing lines constructed using the δD and $\delta^{18}O$ values of water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah. (A) Best-fit mixing line through samples from wells completed in the Navajo aquifer; (B) Best-fit mixing line between isotopic values in oil-field brine samples and make-up water from the alluvial aquifer; and (C) Constructed mixing line between injection water and freshwater from the Navajo aquifer represented by well N6.

Table 9. Percentage of injection water determined from the $\delta^{18}\text{O}/\delta\text{D}$ isotopic mixing model compared with measured and calculated chloride concentration in water from selected wells completed in the Navajo aquifer in and near the Greater Aneth Oil Field, San Juan County, Utah

[Chloride concentration in milligrams per liter; water from well N6 used as fresh end-member water; injection water (mean of PRD1A and PRD4A) used as saline end-member water]

Map number: Refer to table 1 and figure 10.

Map number	Percent injection water	Percent freshwater from well N6	Measured chloride concentration	Calculated chloride concentration from isotopic mixing model
N45	29	71	360	15,500
N18	72	28	4,900	38,500

ues of water from wells completed in the Navajo aquifer in area 1 (fig. 20). The $\delta^{18}\text{O}$ and δD values cannot be used to confirm that water from the upper Paleozoic aquifer is the source of saline water in the Navajo aquifer in area 2 because both water types have similar isotopic values. In contrast, the isotopic enrichment in water from the Navajo aquifer in area 1 is consistent with mixing with the heavier isotopic values of water from three wells completed in the upper Paleozoic aquifer (fig. 20). The correlation between $\delta^{18}\text{O}$ value and chloride concentration in water samples from area 1 ($r^2 = 0.80$, number = 20) is greater than in water samples from area 2 ($r^2 = 0.26$, $n = 25$), supporting the hypothesis that the isotopic enrichment in water from the Navajo aquifer in area 1 is a result of mixing with saline water from the upper Paleozoic aquifer. The elimination of OFB as a source of isotopically enriched (with ^{18}O and D) water in the Navajo aquifer and identification of water from the upper Paleozoic aquifer as a potential source of isotopically enriched (with ^{18}O and D) water in Navajo aquifer samples from area 1 is consistent with trends observed in the bromide, iodide, and chloride data discussed previously.

Strontium Isotopes

Geologists have used strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) to identify sources of igneous rocks for more than 25 years; however, strontium isotope analysis has only recently been applied to ground-water systems (Peterman and Stuckless, 1992, p. 67). Natural variations in the isotopic composition of strontium (abundance of the radiogenic isotope Sr-87 relative to the nonradiogenic isotope Sr-86) dissolved in ground

water were used to provide additional insight into the source(s) of saline water in the Navajo aquifer described previously.

Histograms of $\delta^{87}\text{Sr}$ values of water samples of potential saline end-member sources (OFB and upper Paleozoic aquifer) were compared with a histogram of $\delta^{87}\text{Sr}$ values of water samples from the Navajo aquifer (fig. 21). Strontium isotope values of 56 water samples from the study area are represented in the three histograms. With the exception of two wells (N43 and N44), the $\delta^{87}\text{Sr}$ values of the five OFB samples are substantially smaller than the $\delta^{87}\text{Sr}$ values of water samples from the Navajo aquifer. The median $\delta^{87}\text{Sr}$ value of the OFB data (-1.03 permil) is comparable to the $\delta^{87}\text{Sr}$ value of seawater (about -1.27 permil) during deposition of the Paradox Formation about 300 million years ago (Peterman and Stuckless, 1992, p. 80).

The $\delta^{87}\text{Sr}$ values also were compared with the strontium concentrations in ground-water samples collected in the study area (fig. 22A). Consistent with the results of other geochemical constituents, the $\delta^{87}\text{Sr}$ values of OFB samples are substantially smaller than the $\delta^{87}\text{Sr}$ values of most of the water samples from the Navajo aquifer, indicating that OFB is not the source of salinity to the Navajo aquifer.

In contrast to the OFB samples, $\delta^{87}\text{Sr}$ values of water samples from the upper Paleozoic aquifer are larger, about midway in the range of $\delta^{87}\text{Sr}$ values of water samples from the Navajo aquifer (fig. 21), indicating a possible relation in isotopic signatures. The histogram of $\delta^{87}\text{Sr}$ values of water samples from the Navajo aquifer indicates the presence of two subpopulations that appear to be a function of geographic location. Using a $\delta^{87}\text{Sr}$ threshold value of 0.75 permil to

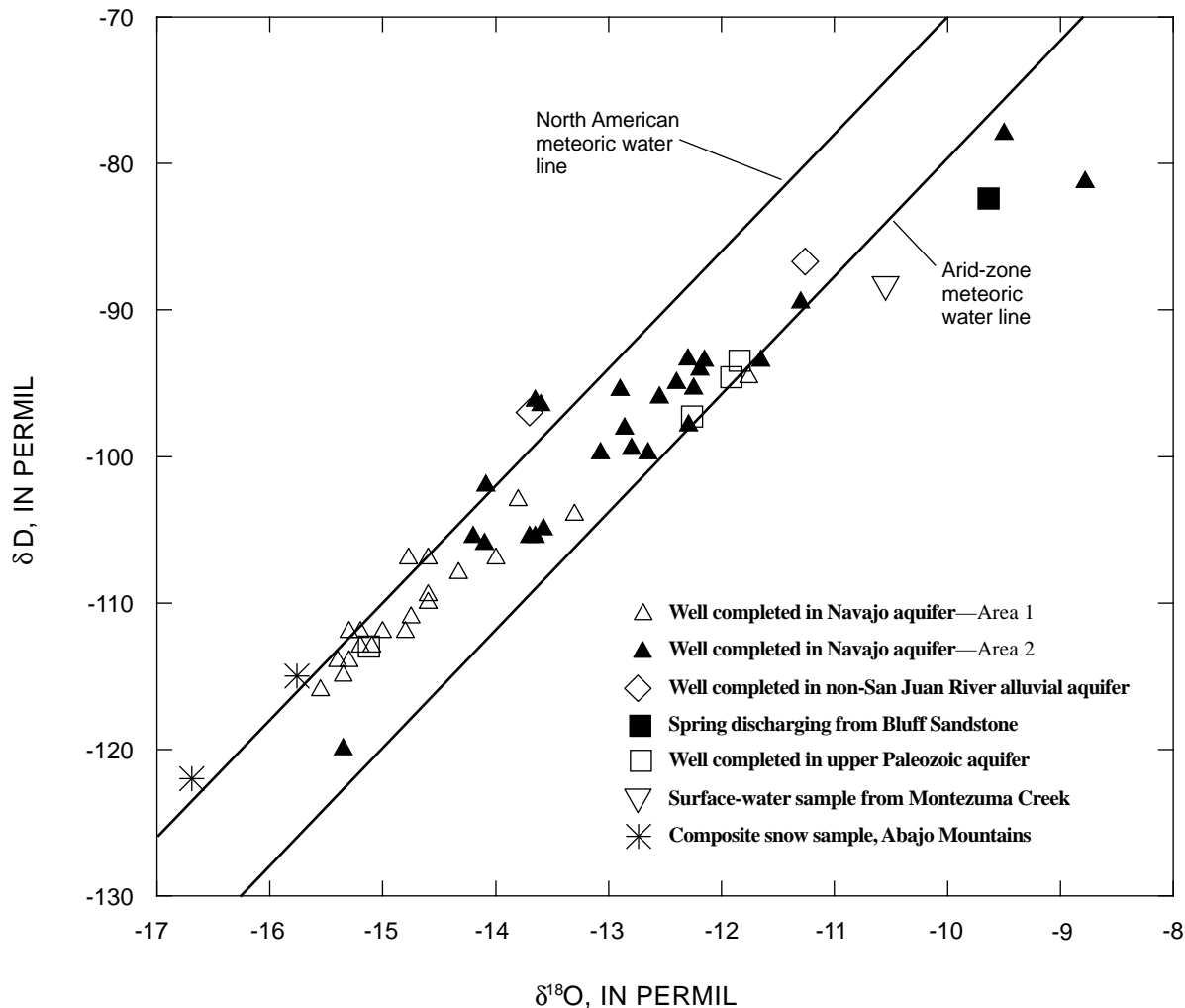


Figure 20. The δD and $\delta^{18}O$ values of water from wells completed in the Navajo aquifer in areas 1 and 2 in relation to the δD and $\delta^{18}O$ values of other water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah.

separate the two subpopulations, the population with a ratio greater than or equal to 0.75 is in the northern half of the study area, and the population with a ratio less than 0.75 is in the southern half of the study area (fig. 22B). The geographic segregation of the data reflects different areas of ground-water movement and is similar to the differentiation indicated by the $\delta^{18}O$ and δD data for water from the Navajo aquifer (fig. 20).

Wells completed in the Navajo aquifer with $\delta^{87}Sr$ values of water greater than 0.75 permil are generally located in the northern part of the study area, and wells with $\delta^{87}Sr$ values of water less than 0.75 permil are located in the southern and eastern parts of the study area (fig. 22B). A north-to-south flow direction (area 1)

is associated with $\delta^{87}Sr$ values greater than 0.75 permil, and east-to-west and south-to-north flow directions (area 2) are associated with $\delta^{87}Sr$ values less than 0.75 permil (fig. 22B). With increasing strontium concentration, areas 1 and 2 appear to converge to the mean $\delta^{87}Sr$ value and mean strontium concentration of four water samples from the upper Paleozoic aquifer (fig. 22A). This convergence indicates that water from the upper Paleozoic aquifer may be a possible source of salinity to the Navajo aquifer and is consistent with geochemical data presented previously.

Mixing models were constructed to more quantitatively investigate the convergence of $\delta^{87}Sr$ values of

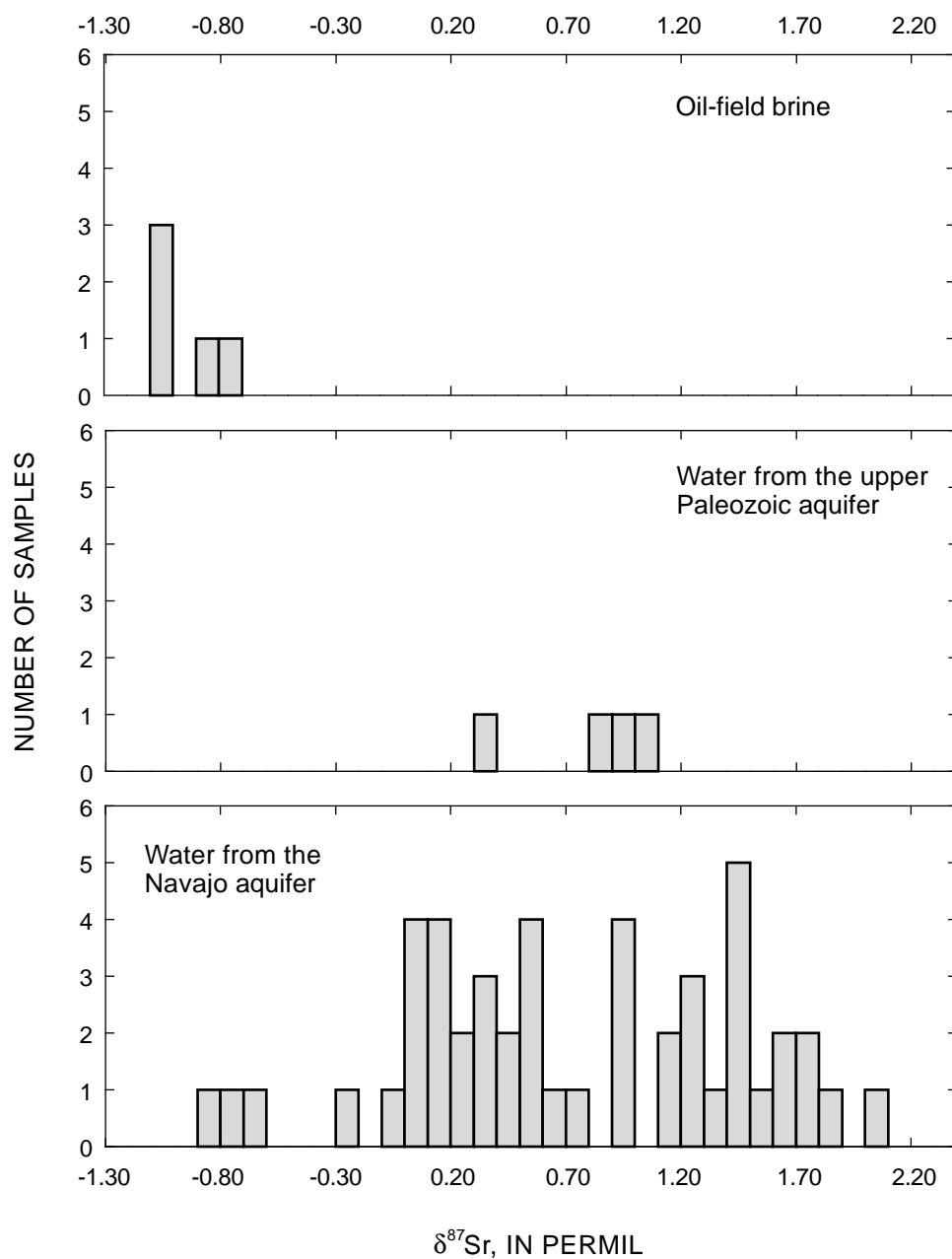
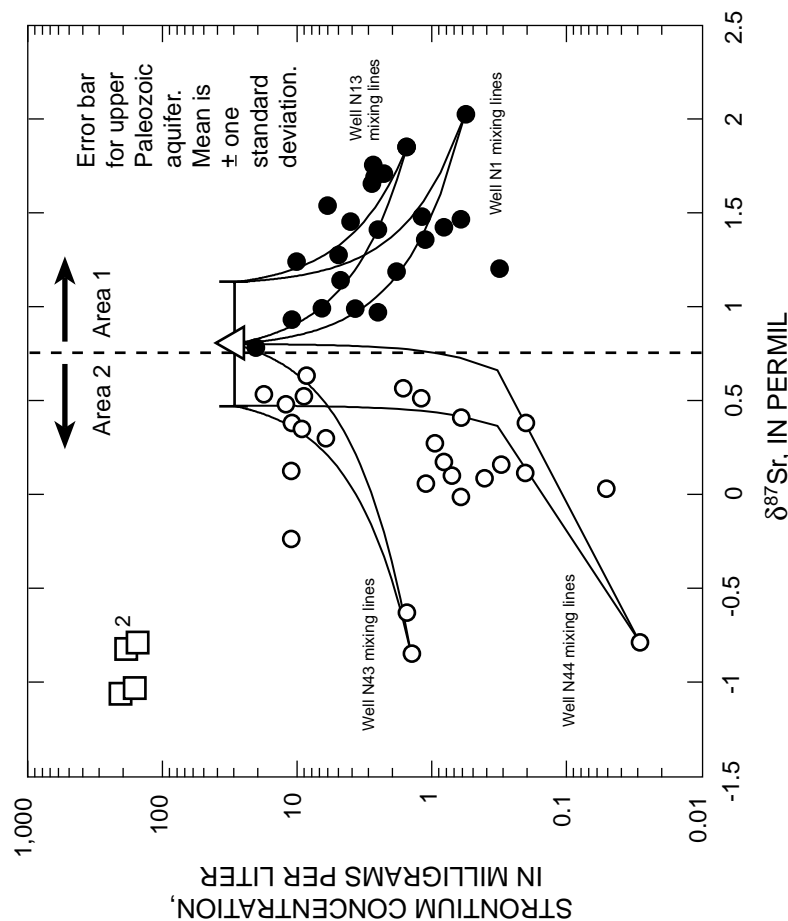


Figure 21. The $\delta^{87}\text{Sr}$ values of oil-field brine and of water from the upper Paleozoic and Navajo aquifers, in and near the Greater Aneth Oil Field, San Juan County, Utah.

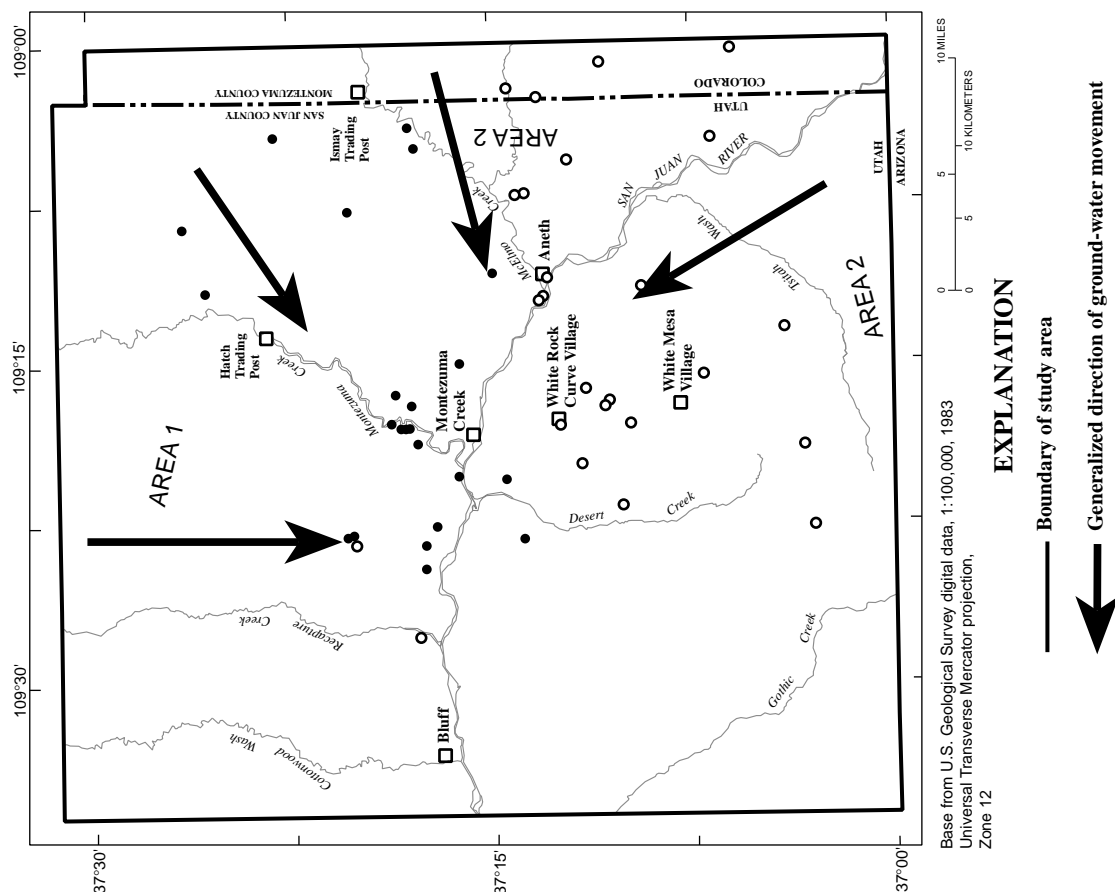
A



EXPLANATION

- Well completed in the Navajo aquifer— $\delta^{87}\text{Sr}$ value greater than or equal to 0.75 permil
- Well completed in the Navajo aquifer— $\delta^{87}\text{Sr}$ value less than 0.75 permil
- ² Oil-field brine sample—Number above symbol refers to multiple analyses
- △ Mean upper Paleozoic aquifer value—Number of samples equals 4

B



EXPLANATION

- Boundary of study area
- Generalized direction of ground-water movement
- Well with $\delta^{87}\text{Sr}$ value greater than or equal to 0.75 permil
- Well with $\delta^{87}\text{Sr}$ value less than 0.75 permil

Figure 22. The relation of ground-water movement to $\delta^{87}\text{Sr}$ value of water samples collected in and near the Greater Aneth Oil Field, San Juan County, Utah. **(A)** Variation of strontium concentration and $\delta^{87}\text{Sr}$ value in relation to eight mixing lines constructed using results of analysis of water from selected wells completed in the Navajo and upper Paleozoic aquifers; and **(B)** Location of wells completed in the Navajo aquifer with large (greater than or equal to 0.75 permil) and small (less than 0.75 permil) $\delta^{87}\text{Sr}$ values. Water from wells in area 1 is generally characterized by $\delta^{87}\text{Sr}$ values greater than 0.75 permil. Water from wells in area 2 is generally characterized by $\delta^{87}\text{Sr}$ values less than 0.75 permil.

water from the Navajo aquifer in areas 1 and 2 (fig. 22A) to the $\delta^{87}\text{Sr}$ composition of water from the upper Paleozoic aquifer. The $\delta^{87}\text{Sr}$ values, in combination with the strontium concentrations, can be used in hyperbolic mixing lines to determine if water from the upper Paleozoic aquifer presents a geochemically consistent salinity source to the Navajo aquifer. Mixing lines were constructed using water samples from four different end-member wells completed in the Navajo aquifer mixed with the mean strontium data from four wells completed in the upper Paleozoic aquifer (fig. 22A). Two end-member water samples were selected from area 1 (N13 and N1) and area 2 (N43 and N44) on the basis of containing low (less than 60 mg/L) chloride concentrations. Water samples with low chloride concentrations were selected because these samples would be most representative of ground water not influenced by mixing with saline water. The $\delta^{87}\text{Sr}$ value of the water samples was a further consideration in selecting non-saline end-member wells. Water samples from wells N13 and N1 have the largest $\delta^{87}\text{Sr}$ values of any water samples in area 1 and water samples from wells N43 and N44 have the smallest $\delta^{87}\text{Sr}$ values of any water samples in area 2. Mixing lines were constructed using the following equations:

$$C_{mix} = C_1 * V + C_2 * (1 - V) \text{ and} \quad (5)$$

$$\delta^{87}\text{Sr}_{mix} = [\delta^{87}\text{Sr}_1 * C_1 * V + \delta^{87}\text{Sr}_2 * C_2 * (1 - V)] / C_{mix} \quad (6)$$

where:

C_{mix} is the strontium concentration of the end-member water mixture,

C_1 is the strontium concentration of the non-saline end-member water,

C_2 is the strontium concentration of the saline end-member water,

V is the volume fraction of the Navajo aquifer end-member water,

$\delta^{87}\text{Sr}_{mix}$ is the strontium isotopic composition of the end-member water mixture,

$\delta^{87}\text{Sr}_1$ is the strontium isotopic composition of the non-saline end-member water, and

$\delta^{87}\text{Sr}_2$ is the strontium isotopic composition of the saline end-member water.

Different values of $\delta^{87}\text{Sr}$ were used to represent the end-member composition of water from wells completed in the upper Paleozoic aquifer. Mixing lines for wells completed in the Navajo aquifer in area 1 used the mean value and the mean value plus one standard deviation, and mixing lines for wells completed in the Navajo aquifer in area 2 used the mean value and the mean value minus one standard deviation (fig. 22A). Eight mixing lines were constructed.

The $\delta^{87}\text{Sr}$ value and strontium concentration from 48 water samples from the Navajo aquifer and 5 samples of OFB were compared with the 8 constructed mixing lines (fig. 22A). The mixing lines generally match the observed trends in areas 1 and 2 using water from the upper Paleozoic aquifer as the source of salinity. The four mixing lines constructed using wells in area 1 (N13 and N1) fit the observed trend of decreasing $\delta^{87}\text{Sr}$ with increasing strontium concentration (fig. 22A). The four mixing lines constructed using wells in area 2 (N43 and N44) also match the observed trend of increasing $\delta^{87}\text{Sr}$ with increasing strontium concentration.

The N13, N1, and N43 mixing lines were used to estimate mixing proportions between the Navajo aquifer end-member and upper Paleozoic aquifer end-member waters in potentially affected wells completed in the Navajo aquifer (table 10). Mixing proportions estimated from the $\delta^{87}\text{Sr}$ models were then used to calculate the chloride concentration expected in the affected wells. Because of the wide variation in chloride concentration in water from the four wells completed in the upper Paleozoic aquifer (1,000 to 15,000 mg/L), the mean chloride concentration was used. The calculated and measured chloride concentrations in water from the affected wells along the selected mixing lines are generally in close agreement, considering the size of the study area and the limited data set (table 10). This agreement between predicted and measured chloride concentrations provides an independent line of evidence supporting the hypothesis that water from the upper Paleozoic aquifer is a possible source of salinity to the Navajo aquifer; however, the larger discrepancies observed in water from selected wells between measured and modeled chloride concentrations could indicate alternate salinity sources or other geochemical processes (aside from mixing) that control chloride concentration.

The location of wells completed in the Navajo aquifer with a $\delta^{87}\text{Sr}$ signature of water from the upper Paleozoic aquifer (mean value plus or minus 1 standard deviation) was compared with the area identified by

Freethey and Cordy (1991, p. 83) where a potential exists for upward movement of water from the upper Paleozoic aquifer into the Navajo aquifer (fig. 23A). Four of the 11 wells completed in the Navajo aquifer containing water with $\delta^{87}\text{Sr}$ values most similar to that of water from the upper Paleozoic aquifer are in the area where the hydraulic gradient indicates a potential for upward movement of water to the Navajo aquifer, and 3 additional wells are within 4 mi of the boundary of this area (fig. 23A). Four of the 11 wells completed in the Navajo aquifer with dissolved-solids concentrations exceeding 6,500 mg/L also are in the area where a potential for upward movement of water from the upper Paleozoic aquifer exists. An explanation(s) as to why four wells with $\delta^{87}\text{Sr}$ values characteristic of water

from the upper Paleozoic aquifer and dissolved-solids concentrations exceeding 6,500 mg/L are located outside the area where a potential for upward movement of water from the upper Paleozoic aquifer exists is unknown. Because the area of potential for upward movement is not well defined (refer to previous discussion), it may be larger than the area shown in figure 23A and may include these additional four wells in the eastern part of the study area.

Water samples from the Navajo aquifer with a $\delta^{87}\text{Sr}$ signature similar to that of water from the upper Paleozoic aquifer generally have the highest dissolved-solids concentrations relative to water samples from other Navajo aquifer wells (fig. 23B). Seven of the 11 wells with dissolved-solids concentrations greater than

Table 10. Percentage of injection water determined from selected $\delta^{87}\text{Sr}$ isotopic mixing models compared with measured and calculated chloride concentration in water from selected wells completed in the Navajo aquifer in and near the Greater Aneth Oil Field, San Juan County, Utah

[Chloride concentration in milligrams per liter]

Map number: Refer to table 1 and figure 10.

Map number	Percent water from upper Paleozoic aquifer	Percent freshwater	Measured chloride concentration	Calculated chloride concentration from $\delta^{87}\text{Sr}$ mixing model
Well N13 mix line				
N50	4	96	520	240
N49	11	89	360	640
N54	18	82	1,300	1,000
N18	35	65	4,900	2,000
N19	71	29	4,700	4,100
Well N1 mix line				
N8	2	98	180	170
N15	4	96	160	290
N10	8	92	460	520
N30	11	89	610	690
Well N43 mix line				
N45	1	99	360	62
N46	21	79	1,100	1,200
N42	29	71	890	1,700
N36	37	63	4,200	2,200

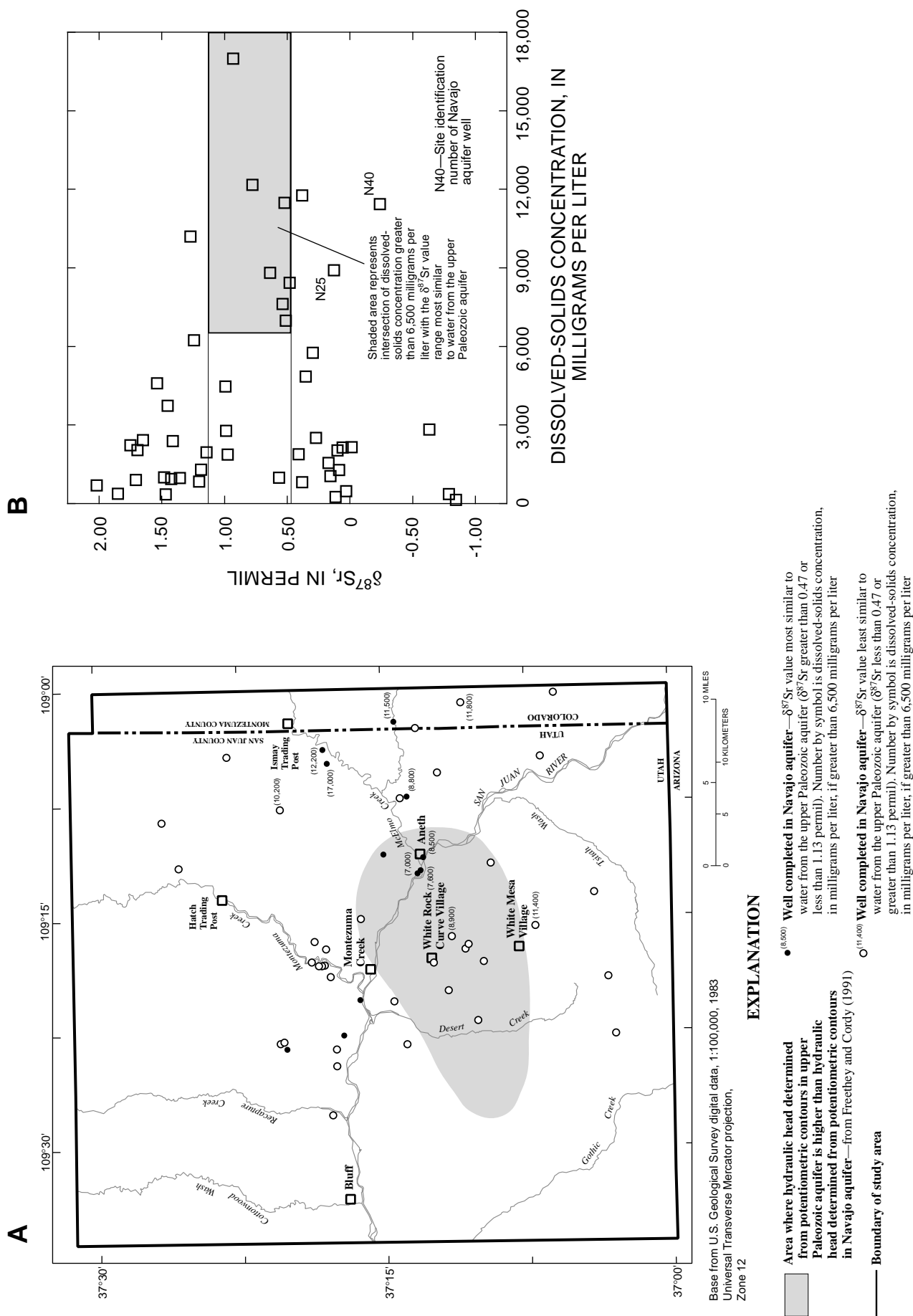


Figure 23. The relation of $\delta^{87}\text{Sr}$ value of water from the Navajo aquifer to that of water from the upper Paleozoic aquifer, in and near the Greater Aneth Oil Field, San Juan County, Utah. (A) Area of potential upward movement of water from the upper Paleozoic aquifer to the Navajo aquifer, in relation to wells completed in the Navajo aquifer with a $\delta^{87}\text{Sr}$ value of water similar to that of water from the upper Paleozoic aquifer; and (B) Variation of $\delta^{87}\text{Sr}$ value and dissolved-solids concentration in water from wells completed in the Navajo aquifer.

6,500 mg/L plot within the range of $\delta^{87}\text{Sr}$ values expected in water from the upper Paleozoic aquifer, and an eighth and ninth well plot close to the expected range (fig. 23B). The $\delta^{87}\text{Sr}$ signature of these nine wells completed in the Navajo aquifer would indicate mixing with a substantial volume of water from the upper Paleozoic aquifer (mean = 11,900 mg/L, number of samples = 4). The remaining two wells (N25 and N40) have a distinctly lighter $\delta^{87}\text{Sr}$ signature than that of water from the upper Paleozoic aquifer. This different signature may indicate mixing with an unknown source(s) of salinity. One possible salinity source could include dissolution of evaporite minerals that may be associated with interdunal lithologies in the Navajo Sandstone; however, as discussed previously, there has been no documented evidence of extensive evaporite deposition in the Navajo aquifer in the study area.

Statistical Similarity Between Ground-Water Samples

Independent interpretation of the bromide, iodide, chloride, $\delta^{18}\text{O}$, δD , and $\delta^{87}\text{Sr}$ data indicates that water from the upper Paleozoic aquifer, not OFB, is a possible source of salinity to water in the Navajo aquifer. Selected water samples from the study area also have been analyzed for 16 additional chemical constituents that can provide further information on the source of salinity to water in the Navajo aquifer. A multivariate data base consisting of analytical results from 52 water samples (43 from wells completed in the Navajo aquifer, 4 from wells completed in the upper Paleozoic aquifer, and 5 OFB samples) collected in the study area was constructed and is referred to as the ANETH data set (table 11). A total of 22 constituents are contained in the ANETH data set, and hierarchical cluster analysis (HCA) was used to extract information from the data set using the software package PIROUETTE (Infometrix, 1992).

The purpose of HCA is to group multivariate data so that underlying links between the groups can be discerned (Davis, 1973, p. 456; and Meglan, 1991). This grouping is accomplished by calculating a similarity distance of all variables contained in the data set between all possible pairs of samples. After sample distances have been computed, the two most similar samples are linked, and this linkage continues until all the samples and clusters have been linked. Identical samples would have a similarity value (SV) of 1.0, and the most dissimilar sample/cluster in the data set would

have a SV of 0.0. Many methods exist for establishing the linkage between samples and clusters, with seven clustering options available in the PIROUETTE software package (Infometrix, 1992, p. 4-6 to 4-7). Results of HCA are displayed in the form of a dendrogram constructed with the SV scale on top decreasing from 1.0 (most similar) to 0.0 (least similar) (fig. 24A).

After log transformation and autoscaling of the ANETH data set, HCA was applied. The complete link clustering option (Infometrix, 1992, p. 4-19 to 4-20) resulted in the most discernible clusters. Three clusters (designated groups 1, 2, and 3) are distinguished using a SV of 0.45 defined by the dotted vertical line on the dendrogram (fig. 24A). The group 3 cluster contains the five OFB samples. Group 1 and 2 clusters contain all the samples from the Navajo aquifer. Three of the four samples from the upper Paleozoic aquifer are in the group 1 cluster, and the remaining sample is in the group 2 cluster.

Separation of the OFB samples from group 1 and 2 clusters containing samples from the Navajo aquifer indicates that OFB is not the salinity source to the Navajo aquifer. If OFB was a contributing salinity source to the Navajo aquifer, a clustering with samples from the more saline wells completed in the Navajo aquifer would be expected. The clustering of 3 wells completed in the upper Paleozoic aquifer with 15 wells completed in the Navajo aquifer (group 1) supports previous results indicating that water from the upper Paleozoic aquifer may be a source of salinity to the Navajo aquifer.

Seven of the 15 group 1 wells completed in the Navajo aquifer are in the area where a potential for upward movement from the upper Paleozoic aquifer exists and 2 other wells are less than 1 mi from the boundary (fig. 24B). This indicates further that the upper Paleozoic aquifer is a geochemically and hydrologically possible source of salinity. Reasons as to why selected group 1 wells are located outside the area where a potential for upward movement of water from the upper Paleozoic aquifer exists are unknown. Because the area of potential for upward movement from the upper Paleozoic aquifer is not well defined, it may be larger than the area shown in figure 24B and could include additional group 1 wells. Group one wells outside of this boundary also could be associated with another source of salinity with a similar geochemical signature as that of water from the upper Paleozoic aquifer. Six wells in the group 2 cluster also are located in the area where a potential for upward movement of water exists (fig. 24B). Dissolved-solids concentrations

Table 11. Data set ANETH used in multivariate statistical analysis

[$\delta^{87}\text{Sr}$, del strontium-87; permil, per thousand; Sr, strontium; mg/L, milligrams per liter; T, water temperature; $^{\circ}\text{C}$, degrees Celsius; TOC, total organic Fe, iron; V, vanadium; Li, lithium; I, iodide; Br, bromide; δD , del deuterium; $\delta^{18}\text{O}$, del oxygen-18; $\delta^{34}\text{S}$, del sulfur-34; Alk, total laboratory alkalinity

Map number: Refer to table 1 and figure 10.

Map number	$\delta^{87}\text{Sr}$ (permil)	Sr (mg/L)	T ($^{\circ}\text{C}$)	TOC (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	F (mg/L)
Wells completed in the Navajo aquifer											
N7	1.42	0.8	19	0.5	8.1	2.7	350	5.7	160	88	1.3
N8	1.35	1.1	20	.2	12	4.4	370	7.1	180	120	1.4
N2	1.48	1.2	19	.2	11	4	360	16	190	110	1.7
N23	1.24	10	18	.1	52	38	2,000	34	1,200	2,600	1.1
N6	1.71	2.3	20.5	.2	19	8.2	290	24	20	230	1.2
N1	2.02	.6	18	.1	6.7	2.7	260	13	57	62	1.1
N51	1.54	5.9	18.5	.2	64	34	1,700	40	1,100	700	.3
N47	.56	1.6	16.5	1.2	2.3	2.3	380	2	240	97	.6
N27	.38	.2	12	9.9	2.5	1	310	2.8	53	150	2.9
N29	.17	.8	18	.2	6.3	1.6	560	3.1	200	500	3.4
N34	.54	18	16	2.3	130	38	2,700	24	3,200	1,200	.7
N33	.51	12	17.5	1.1	120	37	2,400	25	2,900	1,200	.7
N28	.16	.3	19.5	.2	3	0.8	400	2	95	260	3.6
N52	1.45	4	16	1.5	25	7.7	1,400	17	1,100	430	1.1
N16	1.75	2.7	19.5	2.8	24	9.2	840	20	510	230	1.4
N12	1.69	2.6	19.5	.1	23	9.6	780	18	410	220	1.4
N50	1.41	2.5	18	3.1	60	32	840	25	520	360	1.6
N30	.99	3.7	19	.1	23	9.3	1,000	15	610	610	1
N10	.97	2.5	19	.1	23	9.3	690	15	460	200	1.4
N35	.48	12	19	.1	110	42	2,900	31	3,600	1,400	1.1
N20	.10	.7	17.5	1.6	5.1	2.6	750	4.8	240	590	3.3
N14	1.65	2.8	19.5	.5	27	10	850	18	760	300	1.3
N31	-.01	.6	21	.2	4.3	2.5	780	4.9	110	820	3.7
N32	.64	8.5	17	5.5	99	63	2,900	35	3,500	1,800	.9
N15	1.18	1.8	17	.2	20	13	440	20	160	300	1
N36	.38	11	22	.3	170	83	3,900	23	4,200	3,200	2.4
N38	.03	.05	16.5	1.2	1	.3	190	.9	20	47	1.1
N44	-.79	.03	15	.2	.8	.2	150	1	3.6	8.2	1
N13	1.85	1.5	17	.3	22	12	95	15	6.8	46	.5
N46	.30	6.1	20	.4	33	18	1,900	11	1,100	2,400	2.9
N21	.52	9	21.5	45	120	55	3,800	26	1,900	5,400	3.3
N40	-.24	11	19.5	.1	170	73	3,500	21	1,700	5,900	1.4
N48	1.47	.6	19.5	.1	7.4	2.8	120	3.3	19	71	.3
N53	.11	.2	18	1.6	4.2	1.3	90	2.5	6.9	46	.2
N43	-.85	1.4	18.5	.1	10	6.1	38	1.6	3.8	10	.3
N49	1.14	4.8	17	.4	60	32	580	23	360	720	.1
N39	.08	.4	16.5	3.4	3.9	1.2	480	2.4	130	410	2.8
N42	.35	9.1	22	.1	24	12	1,700	10	890	2,000	4.2
N19	.78	20	18	.5	90	79	4,000	35	4,700	3,000	2.3
N41	.06	1.1	21	.1	9.8	4.1	700	4.5	100	1,100	.6
N24	.41	.6	19	3.2	5.3	3.1	750	7	240	630	4.4
N45	-.64	1.5	17.5	.6	11	6.2	990	5.5	360	1,200	2.5
N25	.13	11	17.5	3.2	26	22	2,900	17	2,200	3,500	1.6

carbon; Ca, calcium; Mg, magnesium; Na, sodium; K, potassium; Cl, chloride; SO₄, sulfate; F, fluoride; SiO₂, silica; B, boron; µg/L, micrograms per liter; reported as calcium carbonate]

Map number	SiO ₂ (mg/L)	B (µg/L)	Fe (µg/L)	V (µg/L)	Li (µg/L)	I (mg/L)	Br (mg/L)	δD (permil)	δ ¹⁸ O (permil)	δ ³⁴ S (permil)	Alk (mg/L)
Wells completed in the Navajo aquifer											
N7	11	680	160	2	510	0.021	0.54	-114	-15.30	6.2	529
N8	11	1,100	200	2.3	565	.039	.47	-113	-15.20	4.8	510
N2	10	650	86	1.3	560	.014	.55	-112	-15.00	2.3	507
N23	10	310	2,500	38	1,400	.16	1	-93.5	-12.15	9.7	504
N6	9.4	280	900	.7	390	.006	.11	-113	-15.10	7.5	503
N1	8.8	850	42	.7	480	.005	.09	-114	-15.40	-0.1	484
N51	5.4	1,400	1,500	41	1,110	.062	1.1	-103	-13.80	9.7	1,680
N47	10	200	10	3	140	.022	.25	-107	-14.77	6.1	429
N27	10	890	180	.7	190	.015	.2	-106	-13.70	1.6	475
N29	8.4	1,100	7	2	311	.028	.22	-106	-14.10	6.4	473
N34	9.1	240	2,600	84	1,900	.206	.02	-98.1	-12.86	11.2	454
N33	9.6	230	2,000	83	1,800	.052	3.2	-99.5	-12.80	11.0	438
N28	9.2	1,100	69	.7	311	.01	.16	-106	-14.20	4.7	479
N52	8.4	1,900	30	32	1,400	.012	3.4	-108	-14.33	15.4	1,180
N16	12	1,700	260	9	1,100	.041	.85	-107	-14.60	7.7	992
N12	12	1,600	380	10	960	.038	.79	-110	-14.60	7.6	970
N50	13	1,800	50	12	850	.05	.85	-107	-14.00	8.7	897
N30	10	160	1,600	8.9	820	.075	.55	-104	-13.30	6.1	845
N10	12	1,500	80	10	911	.04	1	-111	-14.75	6.6	770
N35	11	430	1,400	37	2,100	.36	2.4	-96.0	-12.55	9.8	561
N20	9.6	450	80	2.8	510	.024	.26	-96.2	-13.65	5.8	755
N14	10	1,400	80	14	1,100	.012	.65	-110	-14.60	9.7	754
N31	7.9	350	160	400	510	.022	.12	-96.5	-13.60	9.3	753
N32	10	230	11,000	12	2,200	.19	1.5	-95.4	-12.25	10.1	671
N15	8.6	480	110	2.1	410	.019	.16	-112	-14.80	7.0	555
N36	10	2,400	280	98	2,000	.27	3.6	-93.4	-12.30	9.3	260
N38	1.1	200	30	.7	90	.022	.12	-120	-15.35	2.3	352
N44	13	110	13	270	10	.006	.04	-105	-13.58	2.5	327
N13	7.7	200	100	.7	131	.003	.02	-115	-15.35	-7.6	294
N46	8.7	2,500	30	34	1,200	.027	.69	-94.1	-12.19	10.6	419
N21	9.3	3,800	880	49	2,090	.21	.04	-89.5	-11.30	10.3	260
N40	4.7	420	50	34	400	.22	.17	-99.8	-13.07	7.5	104
N48	12	100	37	.7	110	.003	.03	-112	-15.20	-4.1	205
N53	11	40	37	1.6	82	.001	.01	-112	-15.30	-13.5	168
N43	17	50	110	17	20	.003	.05	-78.0	-9.50	2.6	105
N49	10	410	620	4.5	540	.052	.31	-116	-15.55	8.9	294
N39	11	1,200	360	1	300	.015	.21	-106	-13.65	6.6	413
N42	4.7	240	250	19	740	.1	.51	-95.0	-12.40	9.6	359
N19	11	2,800	100	20	3,200	.21	1.5	-97.9	-12.29	9.8	411
N41	10	240	7	2.4	710	.019	.25	-102	-14.09	8.8	404
N24	9.5	170	60	3.9	380	.034	.28	-95.5	-12.90	8.8	392
N45	11	470	30	7.7	640	.066	.45	-99.8	-12.65	11.7	413
N25	9.2	1,000	40	11	280	2.7	1.1	-93.5	-11.65	9.5	389

Table 11. Data set ANETH used in multivariate statistical analysis—Continued

Map number	$\delta^{87}\text{Sr}$ (permil)	Sr (mg/L)	T (°C)	TOC (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	SO ₄ (mg/L)	F (mg/L)
Oil-field brine samples											
PRD3	-1.06	200	24	180	7,700	1,600	52,000	1,100	110,000	1,100	0.9
PRD1	-.82	180	36	6.5	5,700	1,300	22,000	430	48,000	830	1.6
PRD5	-.79	153	27	24	4,400	1,000	20,000	320	48,000	1,700	9.7
PRD2	-1.06	200	13	20	5,000	1,200	20,000	360	44,000	240	3
PRD4	-1.03	160	31.5	5.2	5,800	1,500	24,000	440	48,000	2,000	14
Wells completed in the upper Paleozoic aquifer											
UPZ4	.34	11	32	17	1,400	260	7,900	4.4	15,000	610	.6
UPZ1	1.10	87	27	240	75	11	2,100	1.9	1,000	3,400	1.6
UPZ3	.94	6.4	23	2.8	67	16	860	2.5	1,200	150	1.5
UPZ2	.82	11	30	15	480	120	3,400	1.5	6,000	2,700	.5

in water from wells completed in the Navajo aquifer in the group 1 cluster ranged from 1,970 to 12,200 mg/L, with a median value of 7,620 mg/L. Water from wells completed in the Navajo aquifer in group 2 contains lower dissolved-solids concentrations, ranging from 150 to 3,740 mg/L, with a median value of 1,050 mg/L.

RESULTS AND NEED FOR ADDITIONAL DATA

Although not definitive, hydrologic and geochemical evidence indicates that upward movement of saline water from the upper Paleozoic aquifer to the Navajo aquifer is possible in areas where hydraulic head in the upper Paleozoic aquifer exceeds that in the Navajo aquifer. This conclusion is based on the following observations and interpretations presented previously:

1. Both bromide-to-chloride and iodide-to-chloride ratio mixing models indicate that the mean composition of water from the upper Paleozoic aquifer is a possible source of salinity to water in the Navajo aquifer in the study area. In water from the Navajo aquifer, the bromide-to-chloride and iodide-to-chloride weight ratio decreases with increasing chloride concentration, generally following the end-member mixing lines constructed using the mean composition of water from the upper Paleozoic aquifer.
2. As a result of lower-altitude recharge sources, the $\delta^{18}\text{O}$ and δD values of water from the Navajo aquifer

in the eastern and southern parts of the study area (area 2) have isotopic signatures similar to those of saline water from the upper Paleozoic aquifer. Because of this isotopic similarity, mixing lines cannot be used to identify possible mixing between water from the upper Paleozoic aquifer and water from the Navajo aquifer in area 2. In contrast, the higher-altitude recharge sources of water to the Navajo aquifer in area 1 create a distinctly lighter isotopic signature relative to that of water from the upper Paleozoic aquifer. Isotopic enrichment of water in the Navajo aquifer in area 1 is consistent with mixing with the heavier isotopic values of water from three of the four wells completed in the upper Paleozoic aquifer.

3. The $\delta^{87}\text{Sr}$ signature of the most saline water from the Navajo aquifer is similar to the $\delta^{87}\text{Sr}$ signature of saline water from the upper Paleozoic aquifer. Mixing models developed with the $\delta^{87}\text{Sr}$ data indicate that large volumes of water from the upper Paleozoic aquifer are required to attain the observed salinities. Chloride concentrations predicted using the $\delta^{87}\text{Sr}$ mixing models (water from the upper Paleozoic aquifer as the salinity source) generally agree with measured chloride concentrations in water from selected wells completed in the Navajo aquifer. Four of the 11 Navajo aquifer wells with $\delta^{87}\text{Sr}$ values similar to water from the upper Paleozoic aquifer are located in the area where the hydraulic gradient indicates a potential for upward movement of water to the Navajo aquifer.

Map number	SiO ₂ (mg/L)	B (μg/L)	Fe (μg/L)	V (μg/L)	Li (μg/L)	I (mg/L)	Br (mg/L)	δD (permil)	δ ¹⁸ O (permil)	δ ³⁴ S (permil)	Alk (mg/L)
Oil-field brine samples											
PRD3	5	120,000	1,400	2,400	5,700	47	400	-42.0	2.19	7.8	75
PRD1	25	32,000	850	340	2,500	17	280	-79.0	-6.70	19.0	72
PRD5	16	28,000	130	980	2,900	11	200	-72.3	-7.58	21.5	84
PRD2	27	37,000	3,800	2,500	2,000	18	270	-72.1	-7.51	19.7	643
PRD4	23	39,000	180	400	2,490	17	270	-68.5	-5.60	22.5	158
Wells completed in the upper Paleozoic aquifer											
UPZ4	12	1,500	2,100	420	2,600	1.7	31	-97.3	-12.26	10.7	309
UPZ1	17	1,200	210	29	340	.2	.79	-93.5	-11.84	12.1	246
UPZ3	11	700	510	8.4	530	.14	2.2	-113	-15.12	6.8	372
UPZ2	12	850	160	170	1,200	.53	9.7	-94.6	-11.91	10.3	207

fer and 3 additional wells are within 4 mi of the area where there is a potential for upward movement. Seven of the 11 Navajo aquifer wells with a dissolved-solids concentration exceeding 6,500 mg/L have a δ⁸⁷Sr isotopic signature similar to that of water from the upper Paleozoic aquifer.

- The hierarchical cluster analysis of the ANETH multivariate data set consisted of 52 water samples and 22 chemical and physical constituents and resulted in 3 discernible clusters (designated groups 1, 2, and 3). The clustering of 3 wells completed in the upper Paleozoic aquifer with 15 wells completed in the Navajo aquifer (group 1) supports previous results that water from the upper Paleozoic aquifer may be a source of salinity to the Navajo aquifer. Most (9 of 15) of the group 1 wells completed in the Navajo aquifer are in or near the area where a potential for upward movement of water from the upper Paleozoic aquifer exists, further indicating that the upper Paleozoic aquifer is a geochemically and hydrologically possible source of salinity. Wells completed in the Navajo aquifer in the group 2 cluster are generally located outside the area for upward movement of water from the upper Paleozoic aquifer.
- These results conflict with the conclusions drawn by Kimball (1992) that indicated injection of OFB as the probable source of saline water in the Navajo aquifer. When viewing the conflicting results of the two studies, the following items should be noted:

- Although published in 1992, the Kimball (1992) study was based on data collected more than 10 years ago. The geographic scope of the Kimball (1992) study was much smaller than that of this investigation and the study did not have the water samples, analytical results, and hydraulic-head data from the upper Paleozoic aquifer that were obtained during this study.
- Additional chemical constituents and site-specific samples and analyses of OFB that were obtained during this study were not obtained during the Kimball (1992) study. In particular, Kimball (1992) did not have the strontium isotope or iodide data that were obtained during this study. Without the site-specific analysis of OFB samples that were used during this study, the Kimball (1992) study was not able to use the bromide, iodide, and δ¹⁸O/δD mixing models that indicated the OFB was not the source of salinity to the Navajo aquifer.

Although hydrologic and geochemical data collected and interpreted during this study were used to increase the understanding of the ground-water flow system in this area, additional data collection and synthesis could improve that understanding to fully evaluate the geologic, hydrologic, and chemical factors that have influenced salinization of the Navajo aquifer. Suggestions include (1) using geophysical techniques, such as deep resistivity methods around selected wells, to attempt to identify high-salinity areas; (2) using additional organic and inorganic data from aquifers in

the area in pattern-recognition modeling to “finger-print” brine sources and salinity mechanisms; (3) using carbon isotope data as a dating tool to determine travel times of water in the Navajo aquifer; (4) collecting and updating water-level data from throughout the study area to clarify further the effects of water withdrawal from the Navajo aquifer on possible saline-water migration pathways; (5) further evaluation of the potential for upward movement of water from saline aquifers underlying the Navajo aquifer, particularly along artificial pathways; (6) further investigation of possible effects of depositional systems (for example, interdunal saline lithologies) on local ground-water quality; (7) additional evaluation of the relation between plugged and abandoned wells and areas of high salinity; and (8) investigation of the water chemistry of selected intervals in wells perforated in multiple stratigraphic units.

SUMMARY

Because of the concern of potentially increasing salinity in freshwater aquifers in the vicinity of the Greater Aneth Oil Field in southeastern San Juan County, Utah, the U.S. Geological Survey in cooperation with the U.S. Environmental Protection Agency; Utah Division of Oil, Gas, and Mining; Bureau of Reclamation; Bureau of Land Management; Bureau of Indian Affairs; Navajo Environmental Protection Agency; and the Navajo Water Resources Management Department did a hydrologic and geochemical study to determine the extent and concentrations of salinity in the freshwater aquifers, to document changes in salinity throughout time, and to identify, if possible, the source and potential pathways of the saline water.

Bedrock aquifers in the vicinity of the Greater Aneth Oil Field include those in the Cretaceous Dakota Sandstone, Jurassic Morrison Formation (Bluff Sandstone Member), and the Entrada, Navajo, and Wingate Sandstones. Generally, aquifers in the Bluff, Entrada, Navajo, and Wingate Sandstones are confined in this area, and wells typically discharge water at land surface. The Navajo aquifer, which includes the Entrada, Navajo, and Wingate Sandstones, is the principal bedrock aquifer and generally ranges from 750 to 1,000 feet in thickness, with the top of the aquifer averaging 550 feet below land surface.

The Navajo aquifer is recharged along the flanks of the Abajo Mountains, Sleeping Ute Mountain, and the Carrizo Mountains, to the north, east, and south of the study area, respectively. Potentiometric contours, increasing hydraulic head with depth, and gains in dis-

charge indicate that water in the Navajo aquifer moves downgradient from these recharge areas and moves upward into the Morrison aquifer before discharging into the San Juan River.

Water from the Navajo aquifer is discharged primarily from water wells, and dry holes and previously producing oil wells that were plugged back to water-bearing formations. Measured discharge from flowing wells during the study ranged from less than 1 to as much as 150 gallons per minute. About 600 acre-feet discharged from the Navajo aquifer from flowing wells during 1992-93. Water-level declines in some Navajo aquifer wells have been as much as 178 feet since the 1950s. Discharge from flowing wells also has decreased with declining water levels.

Dissolved-solids concentrations in water from 56 wells in the Navajo aquifer in the study area ranged from 145 milligrams per liter (fresh) to as much as 17,300 milligrams per liter (very saline). Water from most wells shows less than 10-percent variation in salinity with time; however, increases of greater than 50 percent in dissolved-solids concentrations have been documented in water from wells N4, N17, N35, and N45. Decreases in dissolved-solids concentrations in water from some wells in the study area also have been documented.

Dissolved-solids concentrations in water from selected wells and springs in the alluvial, Dakota, and Morrison aquifers ranged from 543 to as much as 3,800 milligrams per liter. Dissolved-solids concentrations in water from selected wells in the upper Paleozoic aquifer ranged from 2,520 to 27,600 milligrams per liter. Water with dissolved-solids concentrations greater than 10,000 milligrams per liter may be less than 500 feet below land surface in the vicinity of the Greater Aneth Oil Field.

On the basis of the relation between water type and salinity, water from the Navajo aquifer containing less than 1,000 milligrams per liter dissolved-solids concentration is generally a sodium bicarbonate type. As salinity increases to about 3,000 milligrams per liter, sulfate and chloride concentrations increase relative to bicarbonate. As salinity increases beyond 5,000 milligrams per liter, water is a sodium chloride sulfate or sodium sulfate chloride type, similar to water from the upper Paleozoic aquifer. Water from aquifers overlying the Navajo aquifer is generally a sodium sulfate bicarbonate type.

High levels of salinity in water from some water wells prior to the late 1950s indicate that saline water was present in the Navajo aquifer before development

of the Greater Aneth Oil Field. Salinity in the Navajo aquifer may have been derived from natural, upward movement of saline water from the upper Paleozoic aquifer or possibly from localized dissolution of evaporites that were present in the Navajo aquifer. Apparent increases and decreases in salinity of water from selected wells could be caused by pumping or wellbore effects. Increases in salinity of water in some wells also could result from potential upward movement of saline water from the upper Paleozoic aquifer through the bores or outside the casings of plugged and abandoned oil wells. Potential upward movement of water from the upper Paleozoic aquifer into the Navajo aquifer may take place in an area near Aneth where the hydraulic head in the upper Paleozoic aquifer exceeds that in the Navajo aquifer.

Bromide-to-chloride ratios indicate depletion in bromide relative to modern ocean water as salinity in water from the Navajo aquifer increases, indicative of mixing with a bromide-depleted salinity source, not characteristic of oil-field brine from the study area. The bromide depletion with increasing salinity generally follows the end-member mixing lines constructed with the mean non-oil-field brine and upper Paleozoic aquifer end-member water compositions. Likewise, as salinity in water from the Navajo aquifer increases, iodide-to-chloride ratios decrease, indicative of mixing with an iodide-depleted salinity source, not characteristic of oil-field brine from the study area. Mixing lines using the mean iodide-to-chloride ratio of water from the upper Paleozoic aquifer best simulate the depletion of iodide with increasing salinity in the Navajo aquifer.

The $\delta^{18}\text{O}$ and δD values of water samples from the Navajo aquifer north of the San Juan River are aligned with the North American meteoric water line and are distinctly lighter than the $\delta^{18}\text{O}$ and δD values of water samples from the Navajo aquifer east and south of the San Juan River, which are more aligned with the arid-zone meteoric water line. Values of oil-field brine and injection water samples plot considerably below both meteoric water lines. The deviation of Navajo-aquifer sample values from the North American meteoric water line is possibly caused by geographic segregation of water in the Navajo aquifer and not by mixing with isotopically enriched (in ^{18}O and D) oil-field brine.

The $\delta^{87}\text{Sr}$ values of oil-field brine samples are substantially smaller than the values of water samples from the Navajo aquifer, indicating that oil-field brine is not a source of salinity. The $\delta^{87}\text{Sr}$ values of water samples from the upper Paleozoic aquifer are similar to the mean isotopic composition of the more saline water from the Navajo aquifer. Seven of the 11 wells completed in the Navajo aquifer with a dissolved-solids concentration exceeding 6,500 milligrams per liter have a $\delta^{87}\text{Sr}$ signature characteristic of water from the upper Paleozoic aquifer. Mixing models using the $\delta^{87}\text{Sr}$ and strontium composition of non-saline water from the Navajo aquifer and saline water from the upper Paleozoic aquifer indicate that the upper Paleozoic aquifer is a possible source of salinity.

Hierarchical cluster analysis using chemical constituents in 43 water samples from the Navajo aquifer, 4 water samples from the upper Paleozoic aquifer, and 5 oil-field brine samples, indicates that oil-field brine is not the salinity source to the Navajo aquifer. The clustering of 3 wells completed in the upper Paleozoic aquifer with 15 wells completed in the Navajo aquifer indicates that water from the upper Paleozoic aquifer may be a source of salinity to the Navajo aquifer.

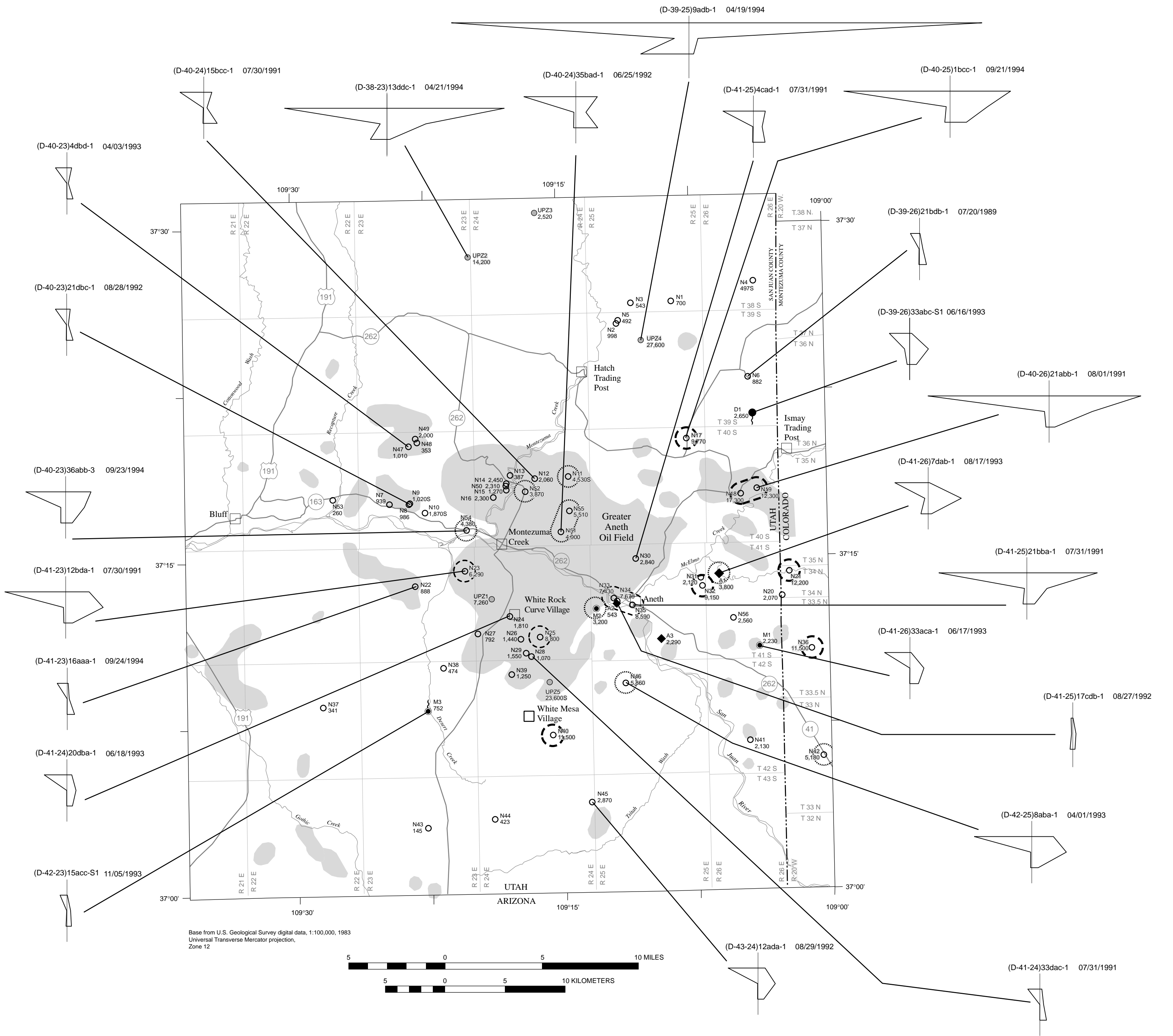
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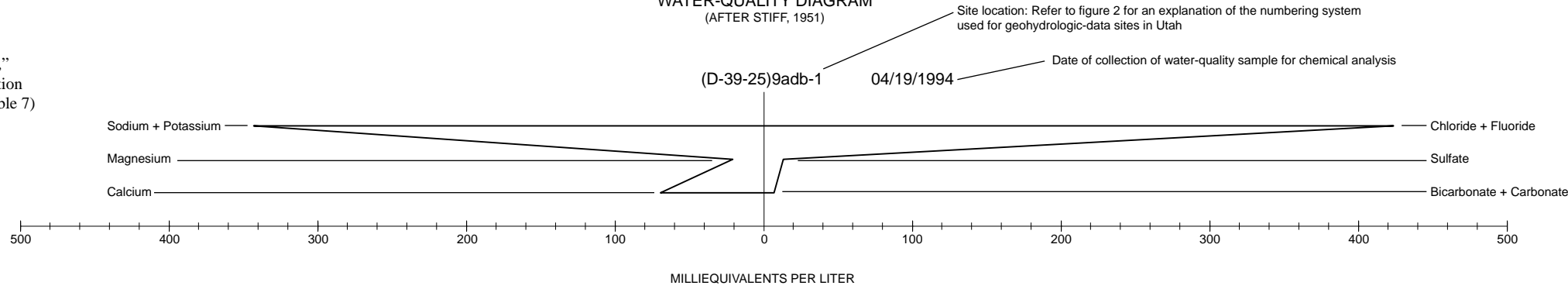
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EXPLANATION

- Area of oil field**
- Dissolved-solids concentration in water from selected wells completed in the Navajo aquifer—mg/L, milligrams per liter**
- Greater than 9,000 mg/L
 - From 6,000 to 9,000 mg/L
 - From 3,000 to 6,000 mg/L
- Boundary of study area**
- Wells and springs**—Top number is site identification number. Bottom number indicates dissolved-solids concentration, in milligrams per liter determined by evaporation at 180 degrees Celsius unless denoted by "S," sum of constituents. Value of dissolved-solids concentration from most recent analysis by U.S. Geological Survey (table 7)
- Well completed in Navajo aquifer
 - Well completed in upper Paleozoic aquifer
 - Well completed in alluvial aquifer
 - Well completed in Morrison aquifer
 - Spring discharging from Morrison aquifer
 - Spring discharging from Dakota aquifer

WATER-QUALITY DIAGRAM
(AFTER STIFF, 1951)



Map showing quality of water from selected wells and springs in the Navajo and other aquifers in and near the Greater Aneth Oil Field, San Juan County, Utah
By
L.E. Spangler, D.L. Naftz, and Z.E. Peterman
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